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# Early season losses of fertilizer nitrogen during corn production

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# Early season losses of fertilizer nitrogen during corn production

by

Kipling Shane Balkcom

A dissertation submitted to the graduate faculty  
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Soil Science (Soil Fertility)

Major Professor: Alfred M. Blackmer

Iowa State University

Ames, Iowa

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## GENERAL INTRODUCTION

Advances in site-specific tools, such as, soil and tissue testing, combined with precision farming technologies (global positioning systems GPS, geographic information systems GIS, remote sensing, and yield monitors) offer new opportunities for evaluating and improving N management during corn production. The improved ability to measure N sufficiency levels (i.e. supply of N relative to the needs of the plant) first described by Macy (1936) that result from specific fertilization practices offer the potential for decreasing energy demands by increasing N efficiency, lowering average rates of fertilization, and preventing environmental degradation of surface and groundwater supplies.

Soil testing for nitrate in late spring provides a measurable index of N availability before plants begin rapid growth (Magdoff et al., 1984; Blackmer et al., 1989; Binford et al., 1992a). Concentrations of nitrate in cornstalks at the end of the season provide another measure of sufficiency levels of N for corn growth at the end of the season (Binford et al., 1990; 1992b). Precision farming technologies allow evaluations of N sufficiency levels as a result of a particular N management practice (i.e. fertilization) on a large scale (Blackmer et al., 1994; White and Blackmer, 1997; Blackmer and White, 1998). These tools used in conjunction with each other enable assessments of N sufficiency levels at different times during the growing season. Knowledge provided by these measurements enables producers to evaluate the effectiveness of N management practices or detect N deficiencies in a timely manner permitting additional N applications before major yield losses occur.

Nitrogen sufficiency levels are affected by soil characteristics, times and methods of application, losses that occur after application, and weather after application. The effect of one factor may be hard to distinguish from the effects of other factors over a wide range of

conditions. However, these site-specific tools allow for evaluations of fertilizer outcomes that encompass the effects of all factors simultaneously. This approach demonstrates how N fertilization practices can be identified that result in optimal sufficiency levels, while eliminating practices that consistently result in below-optimal sufficiency levels, therefore, improving N management.

Applications of liquid swine manure to cornfields represent a potential area where improvements can make a significant impact on N fertilization practices. Liquid swine manures are variable in their composition of inorganic and organic N (Hatfield et al., 1998). Organically bound N must be converted (i.e. mineralized) to inorganic N before plants can use it. Uncertainty arises because the rate at which this mineralization occurs is influenced by site-specific factors, including amounts of manure applied, characteristics of the manure, method of manure application, soil characteristics, and weather after application (Hatfield et al., 1998). Improvement of N management may be accomplished by focusing on mineralization rates of soils after manure application instead of mineralization rates of manure.

Another area of concern in N management is fall-applied N. Recent studies conducted on corn after soybean (*Glycine max* L.) have shown that fall-applied N can be lost soon after application (White and Blackmer, 1997; Blackmer and Ellsworth, 2000; Ellsworth and Blackmer, 2000). These findings illustrate that time and methods of N fertilization are important and influence optimal sufficiency levels. Delaying N applications until plants can effectively utilize N may substantially improve N efficiency (Olson and Kurtz, 1982). Improved N efficiency at sidedress should enhance the correction of N deficiencies.

This project focuses on evaluations of N management practices in production agriculture. The objectives of these studies were to i) describe and conduct preliminary evaluations of a system that utilizes soil and stalk tests in surveys designed to evaluate and improve outcomes of N management practices during corn production, ii) describe a new experimental approach for estimating the net effects of manure on mineralization of N in soils under field conditions, and iii) evaluate the effects of time and method of spring N applications on yield, grain protein concentrations, and canopy reflectance values after fall-applied N applications.

### **Dissertation Organization**

This dissertation is presented as a series of three papers intended for publication. Two papers will be submitted to Agronomy Journal, while the third paper will be submitted to Journal of Environmental Quality. The papers are preceded by a General Introduction and succeeded by a General Conclusion. References cited in the General Introduction are listed in the Literature Cited section immediately after the General Conclusion.

# **SURVEYING OUTCOMES TO EVALUATE AND IMPROVE NITROGEN MANAGEMENT DURING CORN PRODUCTION**

**A paper prepared for submission to Agronomy Journal**

**K.S. Balkcom, A.M. Blackmer, D.J. Hansen, T.F. Morris, and A.P. Mallarino**

## **Abstract**

Survey-type approaches for evaluating and improving management practices during crop production have been described, but they have received little attention in recent years. This report explores the possibility of a system that utilizes soil and tissue tests in surveys designed to evaluate and improve N management during corn production. The study involved analysis of nitrate data from soil sampling in late spring and cornstalk sampling at the end of the season across hundreds of fields in production agriculture over a period of 8 years. Variability in soil and stalk nitrate concentrations were related to rates of N fertilization, applications of animal manure, mean rainfall for Iowa, and mean flows of water in major rivers of Iowa. Analyses of nitrate data from the soils and stalks indicated that losses of N associated with spring rainfall were a major factor affecting sufficiency of N for plant growth. These analyses also showed manure applications supplied less than half of the N needed by corn crops. These findings suggest that surveys of sufficiency levels attained (i.e., the SOSLA approach) can provide important information that producers can use to improve N management practices.

## **Introduction**

Advances in soil and tissue testing offer new possibilities for evaluating and improving the outcomes of N management practices during corn production. Soil testing for

nitrate in late spring provides a measurable index of N availability when plants begin rapid growth (Magdoff et al., 1984; Blackmer et al., 1989; Binford et al., 1992a). Observed relationships between soil nitrate concentrations and crop responses to N make it possible to interpret soil nitrate concentrations in terms of sufficiency of N for plant growth, where sufficiency refers to supply of N relative to the needs of crop (Blackmer, 1999). When used on soils that were fertilized before planting, this soil test evaluates an early outcome of N fertilization practices.

Concentrations of nitrate in cornstalks at the end of the season provide another measure of sufficiency levels of N for corn growth (Binford et al, 1990; 1992b). This test is unique among tissue tests for corn because it reveals excesses of N as well as deficiencies of N during the second half of the growing season. Whereas the soil test assesses sufficiency of N based on the assumption that reasonably normal conditions will prevail during the growing season, the stalk test assesses N sufficiency for plant growth after all factors have influenced N supplies and crop growth at that site. The stalk test, therefore, evaluates the final outcome of N management where the sample is collected.

Although the soil and stalk tests are currently being used, many questions remain concerning how these tests can be used more effectively and the benefits that can be expected. Use of the tests in field experiments is common. However, more information is needed to show how these tests can be used to evaluate and improve N management practices in production agriculture.

A diagnosis and recommendation integrated system (DRIS), originally described by Beaufils (1973), used soil and tissue testing to evaluate and improve management practices. DRIS used a survey-type approach rather than replicated and randomized experiments. It

employs a novel method that uses ratios to diagnose nutrient deficiencies. This approach has received considerable attention (Sumner, 1978; Elwali et al., 1985; Bell et al., 1995) and is often considered as an alternative to methods based on concepts of sufficiency levels described by Bray (1954) and Macy (1936). These techniques have been used to describe the results of replicated and randomized experiments. Although a survey-type approach was used by El-Hout and Blackmer (1990) to evaluate N management practices during corn production, the relative merits of using survey-type approaches have received little attention.

The objective in this study is to evaluate a system that utilizes soil and stalk nitrate tests in surveys designed to evaluate and improve the outcomes of N management practices during corn production. The system is described by the acronym SOSLA (Surveys Of Sufficiency Levels Attained). The system is offered as a complement to existing experimental methods rather than a substitute for these methods.

### **Materials and Methods**

Soil and cornstalk nitrate concentrations were collected across eight years (1988, 1989, 1991, 1995-1999) from cornfields in production agriculture throughout Iowa. Samples were collected by researchers, local agronomists, and farmers. Information about N management practices (i.e., time of application, form of N, method of application, amount of N applied, and manure history) was also collected.

Statewide monthly precipitation data for each year as well as 30-yr means for monthly precipitation data were obtained for Iowa from the National Climatic Data Center (<http://www.ncdc.noaa.gov/onlineprod/drought/xmgrgl.html>). Annual means for flows in the Des Moines River at Keosauqua and the Iowa River at Wapello were obtained from the U.S. Geological Survey (<http://waterdata.usgs.gov/nwis-w/IA/>). The watershed covers

68700 km<sup>2</sup>, nearly 50% of the land area in the state. Most of the samples were collected within this land area. Mean annual flows in these rivers were used as estimates of the relative differences in amounts of water flowing to the Mississippi River in various years.

Soil samples were obtained during all eight years except the 1995 growing season. Soil samples were collected when corn was 15 to 30 cm tall in fields where all fertilizer N was applied before planting (the normal practice in Iowa). The method used to select sampling sites varied slightly among years. The sampling sites within years were selected to provide meaningful comparisons of management practices rather than to provide a random survey of management practices in Iowa. Although the methods used do not provide a valid survey of N management outcomes for Iowa, they do provide valid information concerning relationships between management practices and outcomes. The studies were not initially intended to characterize variability in N sufficiency levels across years, but we believe the methods used are adequate to illustrate the potential of the SOSLA method.

In 1988, 1989, and 1991, soil samples were obtained by combining composite samples from eight cores (3.2 cm diam.) collected to a depth of 30 cm within individual plots. In 1996-1999, soil samples were obtained by combining composite samples from 24 cores (1.7 cm diam.) collected to a depth of 30 cm from uniform areas representing the majority of a field. Samples, from all years, were dried in a forced-air dryer at 49°C. The soils were ground to pass a 2 mm sieve, extracted in 2 M KCl with a 1:5 soil:extractant ratio, shaken for 30 min, and filtered. The filtrates were analyzed for nitrate and exchangeable ammonium by steam distillation described by Keeney and Nelson (1982) or Lachat flow-injection analysis (Lachat Instruments, Milwaukee, WI).

Cornstalk samples were collected 1 to 3 wk after physiological maturity (black layer formation) by cutting a 20 cm segment of stalk beginning 15 cm above the ground from each of 15 plants. Cornstalks were dried in a forced-air dryer at 60°C and ground to pass a 0.5 mm sieve. In all years, except 1999, samples were extracted in 0.025 M  $\text{Al}_2(\text{SO}_4)_3$  with a 1:50 tissue:extractant ratio, shaken for 30 min, and filtered. Nitrate in the filtrates was determined by ion-specific electrode after adding 1 ml of 2 M  $(\text{NH}_4)_2\text{SO}_4$  to each 50 ml of filtrate to reduce differences in ionic strength. In 1999, samples were extracted in 0.5 M KCl with a 1:50 tissue:extractant ratio, shaken for 30 min, and filtered. Nitrate determinations were determined on the filtrates using the same steam distillation procedure used for the soil samples.

Data were analyzed using the regression procedure provided by the Statistical Analysis System (SAS Inst., 1996). Regressions were considered significant when  $\text{Pr} > F$  was equal to or less than 0.05.

## Results

### Soil nitrate concentrations

A significant relationship was found between rates of fertilization and soil nitrate concentrations when data from all years were pooled, but this relationship explained only 4% of the variability in nitrate concentrations (data not shown). Better relationships were found within some years, but these relationships explained no more than 23 % of the variability in soil nitrate concentrations. This finding indicates that other factors had greater effects on soil nitrate concentrations. The finding that fertilizer N accounted for only small percentages of the variability in soil nitrate concentrations can be explained by recognizing that farmers tend to apply fertilizer N at similar rates.



Table 1 summarizes nitrate data from 1556 soil samples collected during seven years. Results from manured and non-manured sites were separated to study the effects of animal manures. Across all sites, the mean rate of N fertilization on manured soils was  $17 \text{ kg N ha}^{-1}$  less than on non-manured soil (Table 1). Some difference in rate should be expected because manure contains N that can be used by crops and because current recommendations encourage farmers to give “credits” for this N when selecting rates of N fertilization (Moffitt et al., 1992; Killorn and Lorimor, 1999). This difference is remarkably similar to the  $15 \text{ kg N ha}^{-1}$  indicated by farmers in a survey described by Duffy and White (1998). The difference in rate of fertilization, however, is much smaller than would occur if farmers believed that manure was applied at rates that provided adequate N for crop growth.

Mean concentrations of soil nitrate across all sites were  $5 \text{ mg N kg}^{-1}$  higher for manured sites than for non-manured sites (Table 1). This difference includes the effects of different rates of N fertilization as well as the effects of N added in the manure. Mass balance calculations indicate that reducing rates of N fertilization by  $17 \text{ kg N ha}^{-1}$  should decrease soil nitrate concentrations by no more than about  $4 \text{ mg N kg}^{-1}$ . The mean effect of added manure on soil nitrate concentrations, therefore, could not have exceeded  $9 \text{ mg N kg}^{-1}$ . Because corn crops require 20 to  $25 \text{ mg kg}^{-1}$  nitrate-N in the surface 30-cm layer of soil before rapid uptake to optimize yield (Blackmer et al., 1989; Bundy and Meisinger, 1994), these calculations suggest manure supplied less than half the N needed by corn crops.

The finding that manure supplied so little N is surprising because there is great concern that manure is applied at rates that supply excess nitrate and thereby pose a threat to water quality (Power and Schepers, 1989; Sharpley et al., 1998). The results of the soil test indicate that either farmers apply manure at rates much lower than recommended or current

recommendations underestimate the amounts of nitrate formed from manure. It seems unlikely producers are applying rates of manure less than recommended rates.

Recommended rates are intended to supply adequate N and it is to the producer's economic advantage to apply manures at rates that are high enough to supply adequate N for plant growth

When compared to sites without manure, sites with manure had smaller percentages of samples in the low and optimal categories, and greater percentages of sites in the high category. This distribution of soil nitrate concentrations indicates that farmers applied too much fertilizer N at some sites. However, this distribution also indicates that farmers applied too little N at some sites. This distribution indicates uncertainty in amounts of N needed because it would be irrational for farmers to knowingly apply too little or too much N. Amid this uncertainty, it must be recognized that farmers may have applied too much fertilizer N because economic analyses indicate that historically farmers are well advised to increase N rates under conditions of uncertainty (Barber, 1973; Babcock, 1992). Recommendations that reduce uncertainty in fertilizer needs should decrease average rates of N fertilization.

#### **Stalk nitrate concentrations**

Table 2 summarizes data obtained from analyses of 1662 stalk samples collected in the 8 years included in this study. Information concerning numbers of samples and rates of fertilization are slightly different than reported in Table 1 because stalk samples and soil samples were not always collected at the same sites. However, differences in rates of fertilization for the manured and non-manured soils were similar to those in Table 1.

Concentrations of nitrate in cornstalks were higher on the manured soils than the non-manured soils (Table 2). This difference includes the effects of different rates of N

fertilization as well as the effects of N in the manure. The manured soils had smaller percentages of samples falling in the low and optimal categories and higher percentages in the high category. These findings confirm observations based on the soil nitrate concentrations in late spring. Use of either method alone would have resulted in essentially the same conclusion, but the results of a single method have much less credibility than the results that show agreement by two independent methods.

#### **Variability among years**

Results from soil testing in late spring and from cornstalk testing in the fall indicated marked variability in mean nitrate concentrations between years. Indeed, the CVs for annual means for soil nitrate and cornstalk nitrate were about twice the CVs of commercial N applied. These observations suggest that some factor (or factors) associated with years was (were) more important than the effects of fertilizer N or applications of manure.

Regression analyses showed that annual mean concentrations of soil nitrate tended to decrease with increases in mean amounts of rainfall that occurred in Iowa (Fig 1). These relationships are not surprising because it has long been known that rainfall promotes losses of nitrate from soils by leaching and denitrification. Relationships based on rainfall during the calendar year (Fig. 1A) were not as good as relationships based on rainfall occurring during March through May (Fig. 1B). This difference should be expected because the soil samples were collected in early June, which is closer to the March through May period. The results provide evidence that losses of N associated with early-season rainfall were a major factor affecting supplies of nitrate in soils when plants began rapid growth.

Mean concentrations of stalk nitrate for years also decreased with increased annual rainfall (Fig. 2A). The relationships were improved if only March through May rainfall were

considered (Fig. 2B). This observation supports results of the soil test by indicating that substantial amounts of plant-available N were lost before soils were sampled in early June. The relationships with the stalk data (Fig. 2) were curvilinear compared to relationships with the soil test data (Fig. 1), but this should be expected because relationships between stalk nitrate concentrations and rates of N fertilizer are non-linear (Blackmer and Mallarino, 1996). Factors such as weather after soil samples are collected, corn hybrid, planting density, weed populations, and severity of damage caused by insects or diseases may have contributed to the non-linear relationships observed between stalk nitrate concentrations and rainfall.

Regression analyses showed that annual means for concentrations of soil and stalk nitrate decreased with increased amounts of water that flowed through major rivers in Iowa (Figs. 3 and 4). This finding can be explained because annual means for water flow in rivers were correlated with annual means for rainfall (Fig. 5). Relationships between water flow in rivers and soil nitrate concentrations had  $r^2$  values similar to relationships found between soil nitrate concentrations and rainfall (Fig. 3). Relationships between water flows in rivers and stalk nitrate concentrations (Fig. 4) were improved compared to relationships between rainfall and stalk nitrate concentrations (Fig. 2).

The finding that mean annual losses of N from soils increased with increases in mean annual rainfall and flows in rivers helps explain the observation that annual mean concentrations of nitrate in Iowa rivers increased with an increase in annual mean water flow in the rivers (Keeney and DeLuca, 1993). Such relationships indicate that additional rainfall may leach soil nitrate rather than merely dilute nitrate from existing sources. The observed effect of rainfall on soil nitrate concentrations supports the assumption of Lucey and Goolsby (1993) that increasing amounts of rainfall prompt greater losses of nitrate from agricultural

fields to rivers. However, the observed effects of rainfall on soil nitrate concentrations indicate that early season losses of N are most important.

#### **Dry versus wet years**

Figure 6 shows mean monthly rainfall of 1988 and 1989, mean monthly rainfall of 1991 and 1999, and mean monthly rainfall of the past thirty years. Data for 1988 and 1989 were selected to represent relatively “dry” growing seasons for Iowa, and data for 1991 and 1999 were selected to represent relatively “wet” growing seasons for Iowa. The means show marked differences in amounts of rainfall that occurred early in the growing season, before plants had an opportunity to use significant amounts of fertilizer N applied before planting. Rainfall usually exceeds evapotranspiration during this period, so excess water is most likely to move through soils at this time.

Data presented in Fig. 7 shows the frequency distributions for soil and stalk nitrate concentrations observed on the wet and dry years. The observed distributions of soil and stalk nitrate concentrations clearly were influenced by rainfall. The observed distributions also indicate that other factors were also important. Amounts of rainfall at individual sites, as opposed to statewide means, should be considered an important factor. Other factors may include rates and times of manure or fertilizer application and soil characteristics (pH, organic matter, texture, slope, etc). Although insufficient data were collected to provide a reasonable assessment of the importance of each of these factors, the results clearly indicate that the effects of spring rainfall were extremely important across the range of conditions studied.

## Discussion

The observed relationships between mean rainfall amounts for March through May and soil nitrate concentrations measured in late spring explained 74% of the variability in annual means of soil nitrate concentrations between the fields studied. The effects of rainfall, therefore, are important when trying to explain differences among sites and years in corn responses to fertilizer N that is applied before planting. Indeed, these effects are sufficiently important that attempts to explain variability in the effects of fertilization on crop growth would seem futile unless the effects of rainfall are considered. The finding that these effects are easily detected by the SOSLA method is noteworthy because important effects of rainfall should be expected, but early season rainfall has not emerged as a key factor in analyses of data collected in response trials conducted at various locations.

The finding that early season rainfall is a key factor influencing the effectiveness of current N fertilization practices provides important information that can be used to improve N management. This finding indicates that substantial benefits could be obtained by delaying fertilization until plants need this N during the growing season. These delays could be expected to reduce average rates of fertilization needed to maximize yields and reduce variability among sites and/or years in amounts of fertilizer N needed. Evidence to support this conclusion is provided by recent studies (Blackmer and Ellsworth, 2000; Ellsworth and Blackmer, 2000; White and Blackmer, 1999) that use precision farming technologies to identify optimal rates of N fertilization for corn after soybean in large-scale field trials. The observed effects of early season rainfall explain why average rates of fertilization and problems associated with soil spatial variability among sites can be reduced by shifting from pre-plant to in-season fertilization.

Analyses of the effects of manure and rates of N fertilization demonstrate the ability of the SOSLA approach to evaluate cultural practices or recommendations. Collection of soil and stalk samples from numerous sites can evaluate the ability of a given practice or recommendation to produce the desired outcome (i.e., to attain optimal levels of N sufficiency). The power of the SOSLA approach becomes evident if one considers the difficulty and costs associated with designing a series of response trials that would provide a sensitive evaluation of the hypothesis that a specified recommendation underestimates the effects of manure on N availability to the first crop.

The power of the SOSLA approach also is evident when it is recognized that the data collected can be used to generate recommendations for N management. The SOSLA approach is especially well suited to the task of making site-specific recommendations. Relatively few samples are needed, for example, to evaluate the outcomes of management under a narrow range of conditions (i.e., small geographic area, single rate and method of application, similar soils and management practices). Although standards are not yet developed to enable evaluations of management in absolute terms, it is relatively simple to compare the outcomes of alternative practices within a narrow range of conditions. Site-specific information is valuable because it focuses on factors important at that site and thereby avoids factors that are important only at other sites. Site-specific recommendations, therefore, avoid much of the uncertainty found in recommendations developed from data collected across a wide range of conditions.

The SOSLA approach characterizes the variability in management outcomes across the range of conditions studied and focuses on identifying the most important causes of variability in this range of conditions. The SOSLA approach can be used to answer questions

about the effects of specific factors and to assess the importance of these factors within a narrow range of conditions. The importance of the effects of each factor, however, always is evaluated within the context of other important sources of variability across the range of interest. This approach makes it easier to organize new findings into a coherent body of knowledge than does an approach that focuses on the learning about effects of one or two factors in experiments carefully designed to minimize the effects of all other factors.

### **Conclusions**

Survey-type approaches offer great potential for improving N management practices in production agriculture. New soil and tissue tests make it possible to efficiently evaluate the outcomes of N management in terms of sufficiency levels attained. Key advantages of this approach are that all sources of variability in outcomes are studied and analyses focus on identifying the most important factors. It is possible to focus on the effects of a single factor under a relatively narrow range of conditions, and the importance of any factor always is evaluated in relation to other factors. This makes it easier to organize observations into a systematic body of knowledge, even when management practices are continuously changing. Individual producers can use the method to improve N management on their fields, but aggregate analyses of data collected across many farms can be used to identify the best practices. Perhaps the greatest advantage of this method is that groups can develop specific recommendations for a specific geographic area as opposed to relying on more general recommendations that may not apply to that area.

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Table 1. Mean soil nitrate concentrations and total commercial N applied for manured and non-manured samples across seven years.

Year	No. of samples		Comm. N applied				Soil nitrate				Percentage within categories†							
	-‡	+§	-		+		-		+		Low		Marginal		Optimal		High	
			M¶	CV	M	CV	M	CV	M	CV	-	+	-	+	-	+	-	+
			kg N ha <sup>-1</sup>				mg N kg <sup>-1</sup>				%							
1988	101	70	184	31	150	39	42	49	41	39	0	0	11	9	15	21	74	70
1989	95	84	165	31	155	37	44	50	53	51	0	4	11	10	25	4	64	83
1991	81	37	147	29	110	40	23	65	23	55	21	16	23	24	35	27	21	32
1996	93	67	122	42	124	44	21	67	27	63	18	16	31	27	32	21	18	36
1997	177	63	118	46	87	60	30	72	35	68	10	3	27	25	25	21	38	51
1998	232	63	149	23	134	24	18	97	27	86	41	24	28	17	12	27	19	32
1999	341	49	155	19	164	15	16	58	21	51	27	16	44	31	21	27	9	27
mean	160	62	149		132		28		32		17	11	25	20	24	21	35	47

† Low (<10 mg N kg<sup>-1</sup>), marginal (10-19 mg N kg<sup>-1</sup>), optimal (20-29 mg N kg<sup>-1</sup>), and high (>29 mg N kg<sup>-1</sup>)

‡ No manure

§ Manure

¶ Means

Table 2. Mean stalk nitrate concentrations and total commercial N applied for manured and non-manured samples across eight years.

Year	No. of samples		Comm. N applied				Stalk nitrate				Percentage within categories†					
											Low		Optimal		High	
	‡	§									-	+	-	+	-	+
			Mean	CV	Mean	CV	Mean	CV	Mean	CV						
			-----kg N ha <sup>-1</sup> -----				-----mg N kg <sup>-1</sup> -----				-----%-----					
1988	97	59	184	32	153	39	4643	57	5139	65	1	0	15	20	84	80
1989	77	74	161	35	152	40	7266	50	7824	38	5	0	6	3	89	97
1991	81	37	147	28	110	40	2646	112	2799	114	26	35	27	24	47	41
1995	140	66	147	57	113	61	1089	112	2356	100	30	17	51	39	19	44
1996	342	116	143	22	143	35	2220	94	3176	81	16	16	41	26	43	59
1997	128	29	143	34	85	62	2203	93	2052	88	13	21	45	38	43	41
1998	36	8	151	21	178	38	1116	117	2120	141	47	38	33	25	19	38
1999	331	41	162	40	157	15	1475	131	2177	117	38	34	33	29	30	37
mean	154	54	155		136		2832		3455		22	20	31	26	47	55

† Low (<250 mg N kg<sup>-1</sup>), optimal (250-2000 mg N kg<sup>-1</sup>), and high (>2000 mg N kg<sup>-1</sup>)

‡ No manure

§ Manure

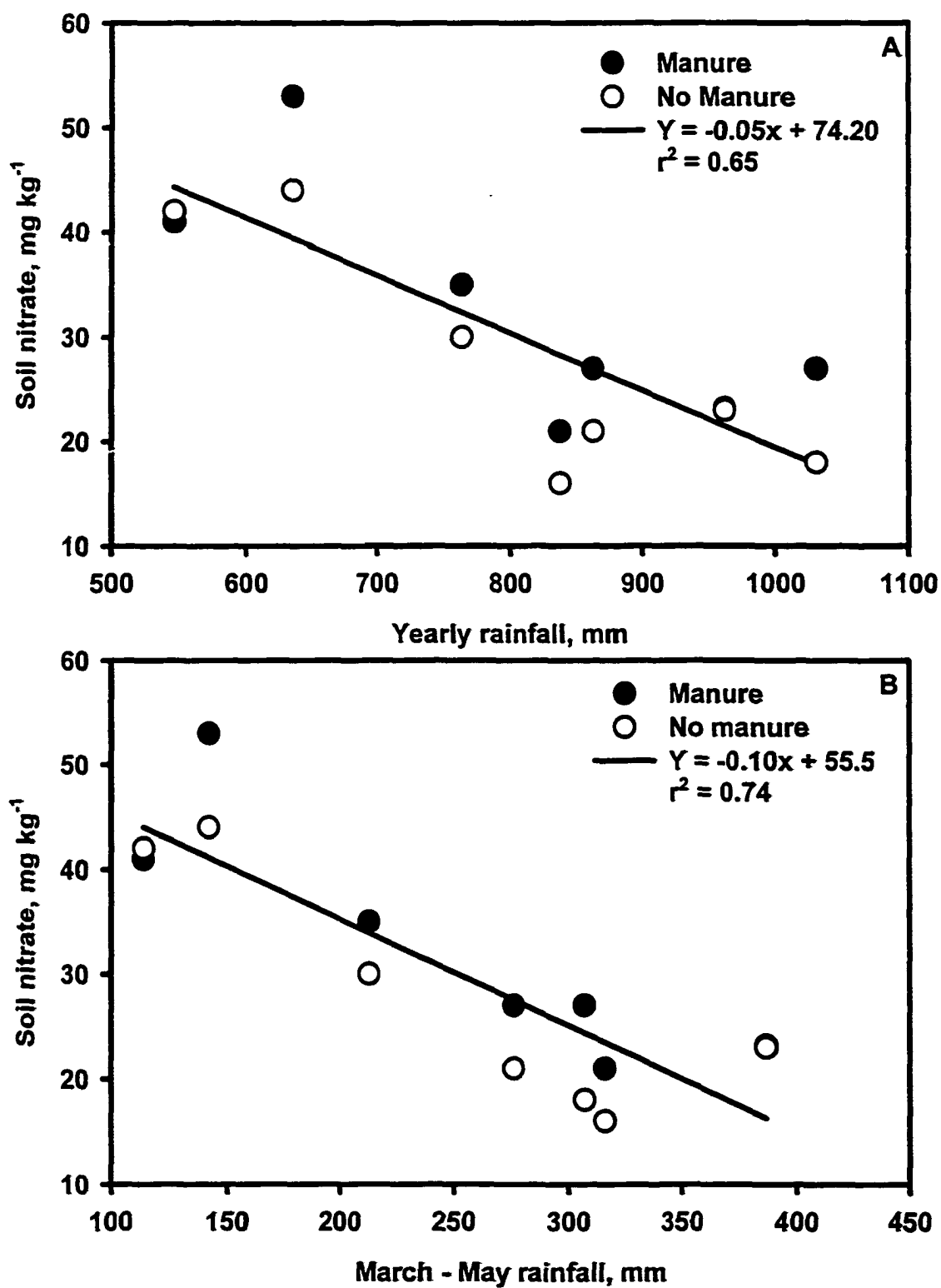


Figure 1. Mean soil nitrate concentrations for manured and non manured soils plotted against yearly rainfall (A) and March-May rainfall (B).

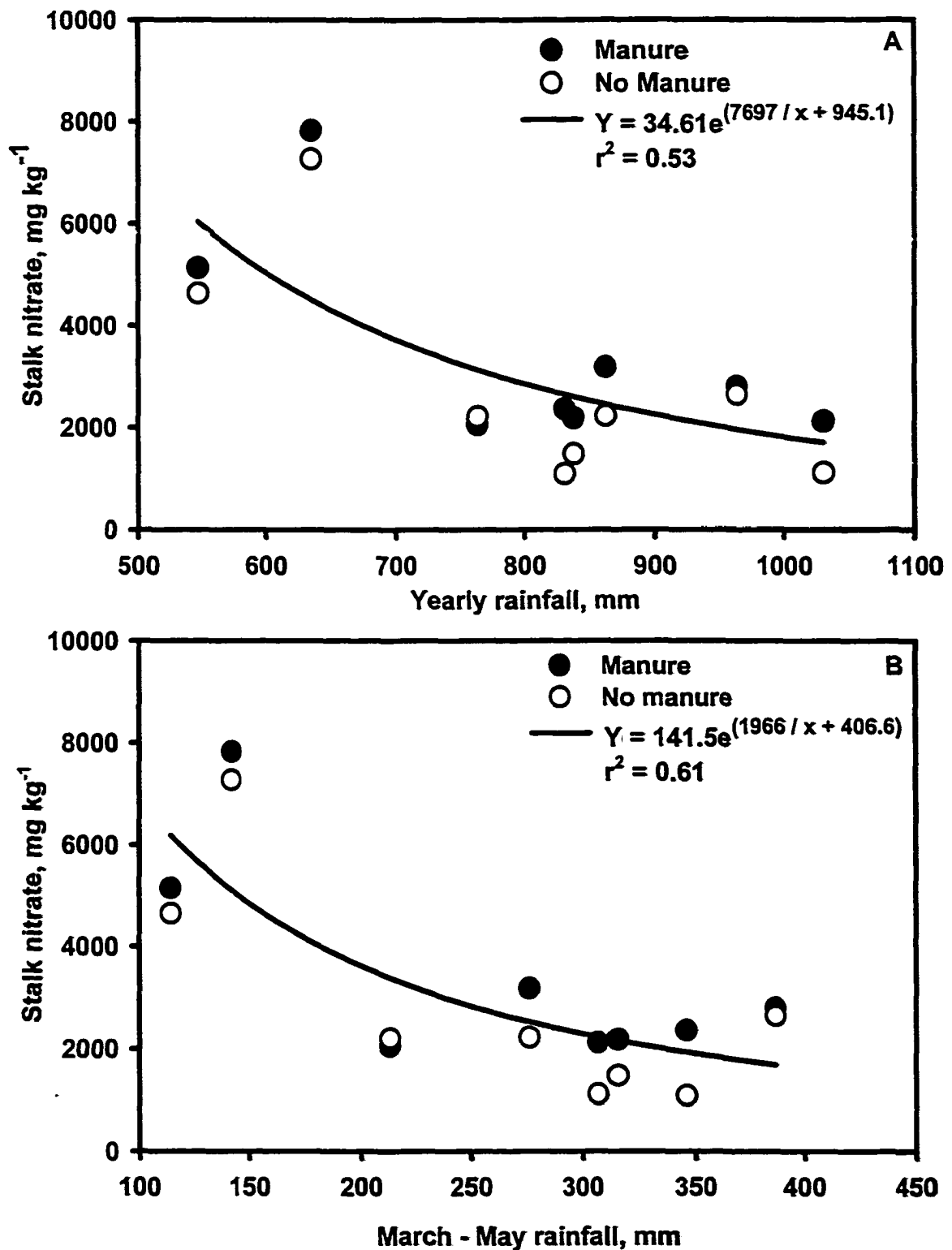


Figure 2. Mean stalk nitrate concentrations for manured and non manured soils plotted against yearly rainfall (A) and March-May rainfall (B).

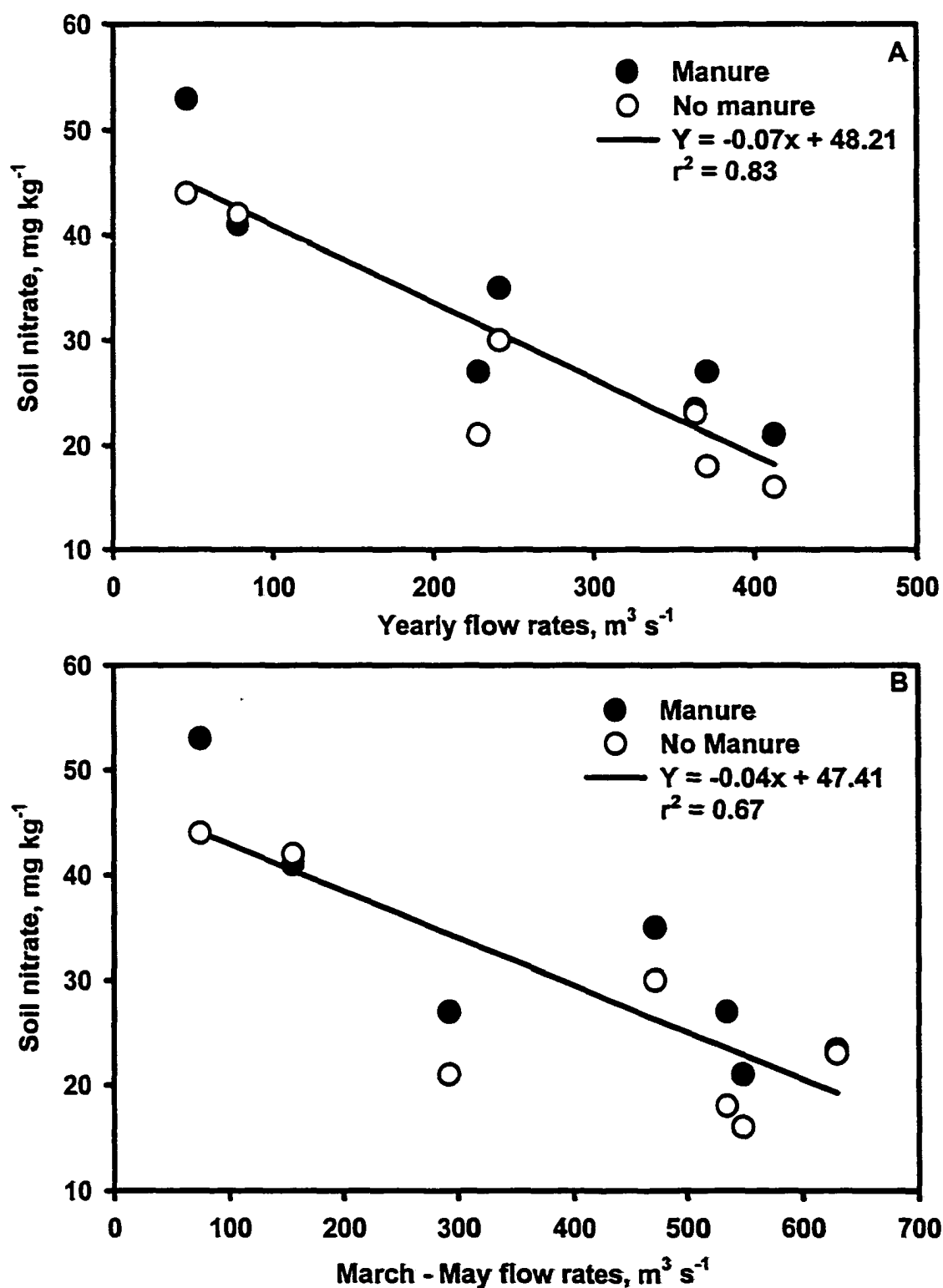


Figure 3. Mean soil nitrate concentrations for manured and non manured soils plotted against mean yearly flow rates (A) and mean March-May flow rates (B) of the Des Moines and Iowa Rivers.



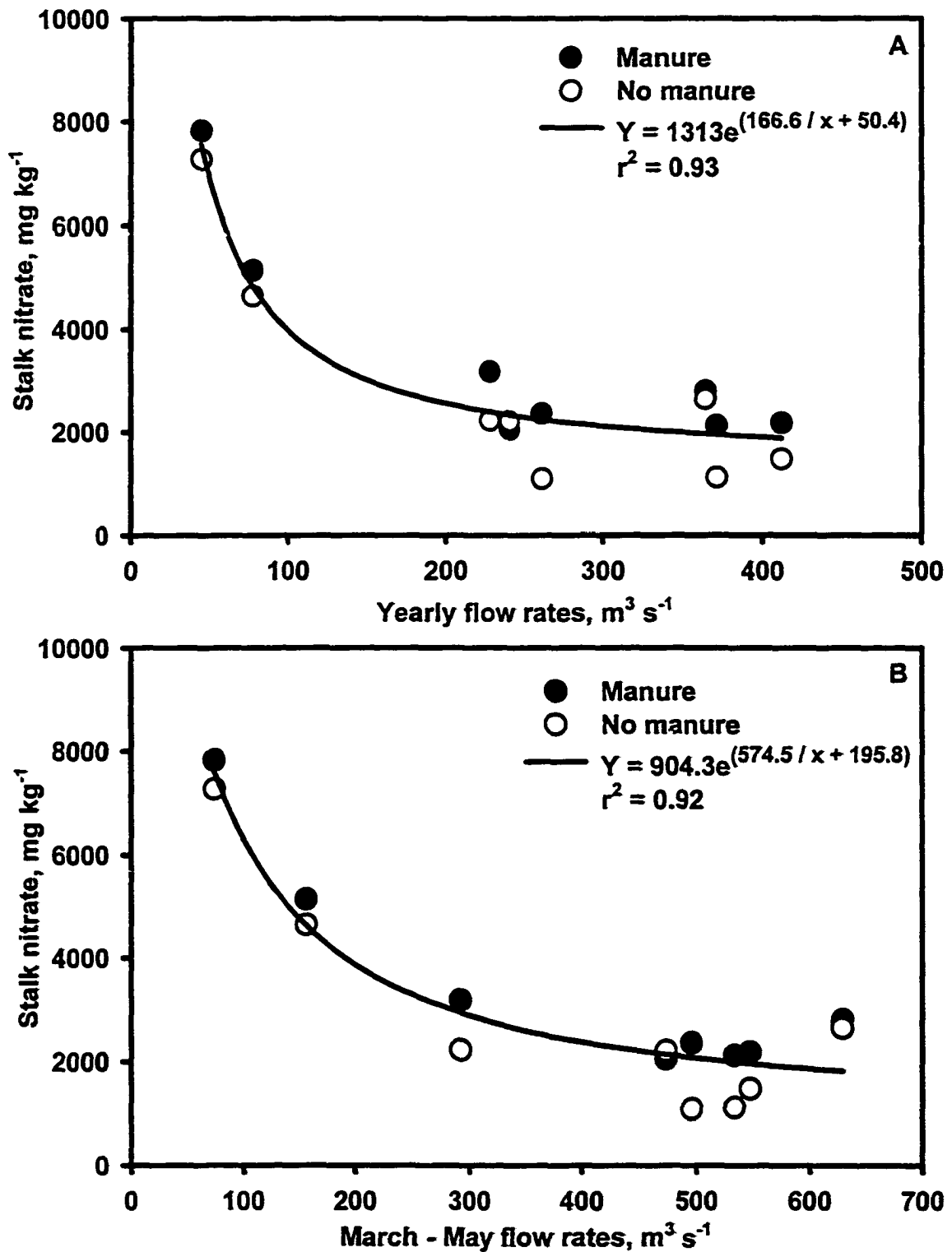


Figure 4. Mean stalk nitrate concentrations for manured and non manured soils plotted against mean yearly flow rates (A) and mean March-May flow rates (B) of the Des Moines and Iowa Rivers.

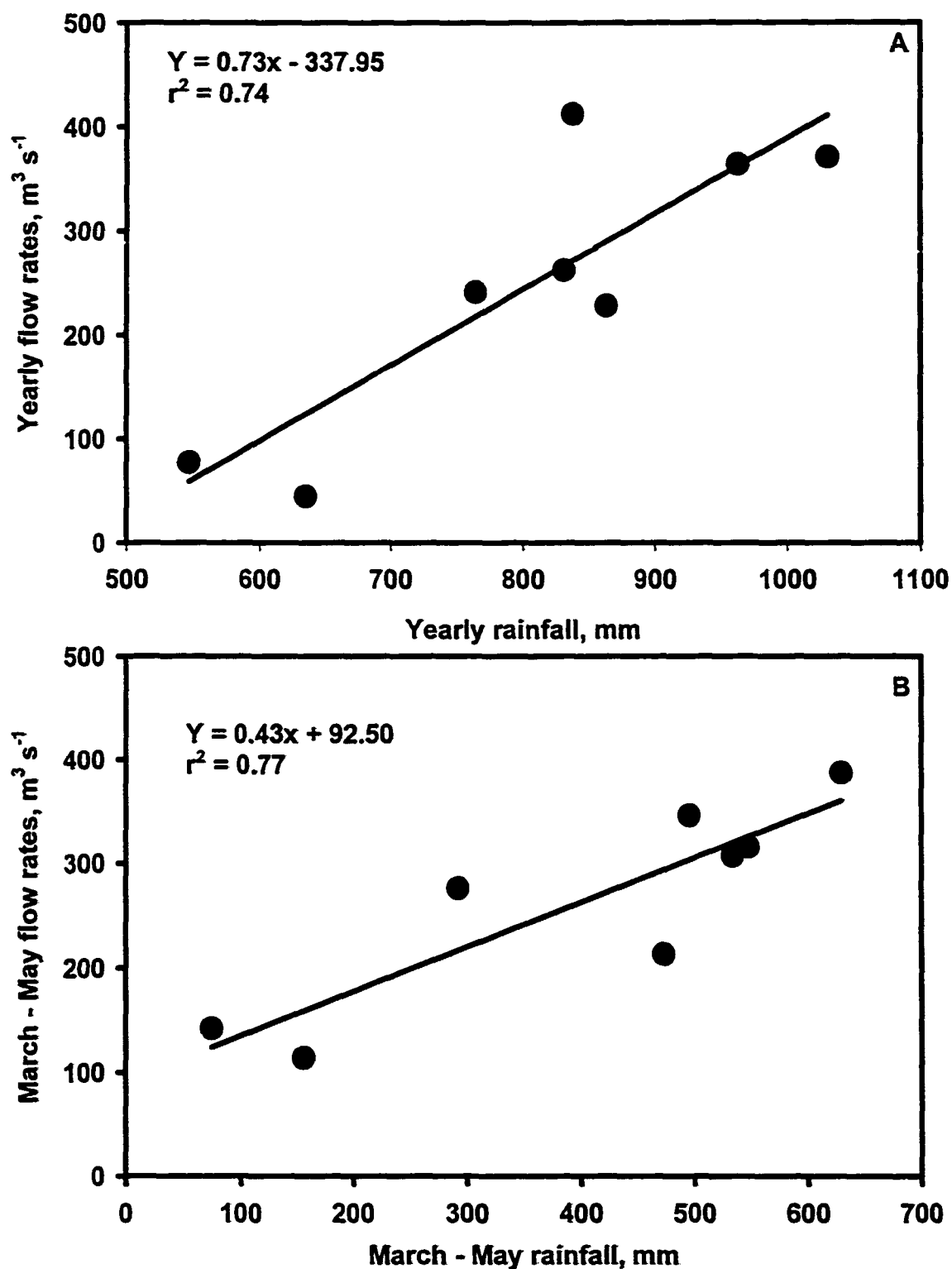


Figure 5. Relationship between mean yearly rainfall and mean yearly flow rates of the Des Moines and Iowa Rivers (A) and relationship between mean March-May rainfall and mean March-May flow rates of the Des Moines and Iowa rivers (B).

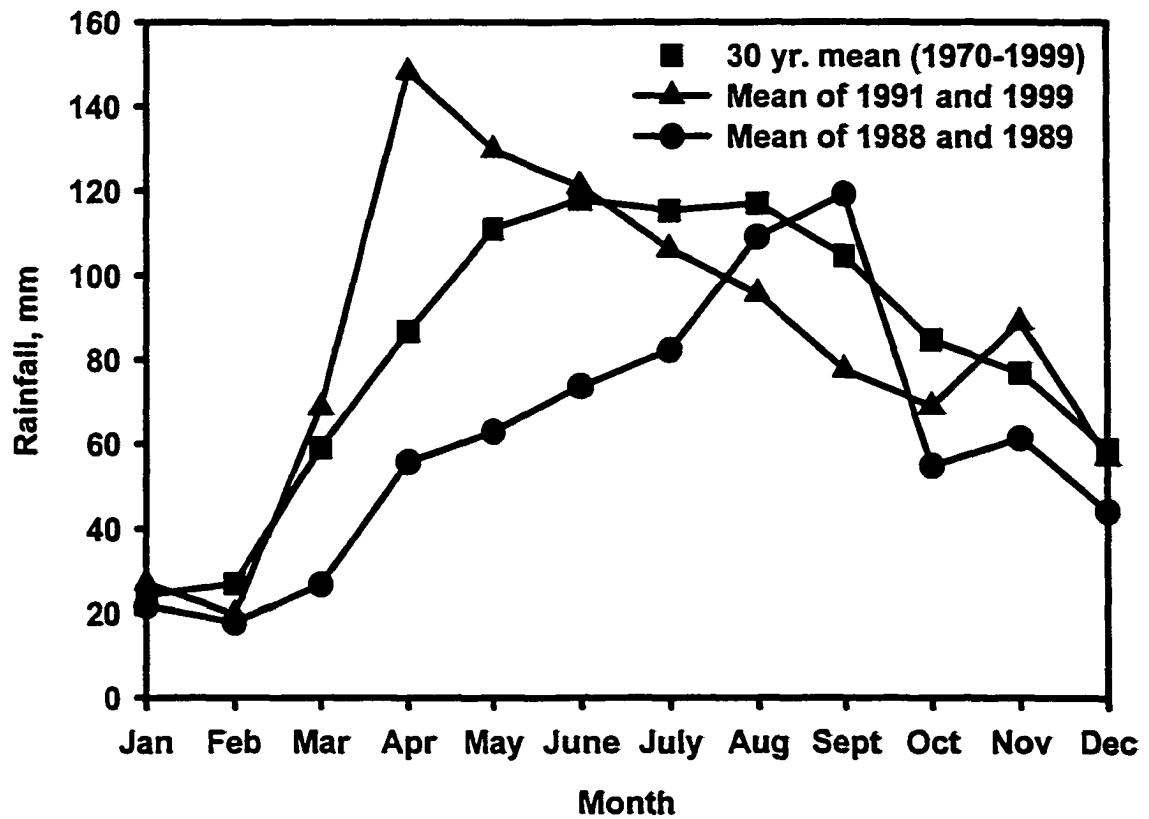


Figure 6. Mean monthly rainfall of 1991 and 1999 and mean monthly rainfall of 1988 and 1989 plotted against the 30 yr average of rainfall for Iowa.

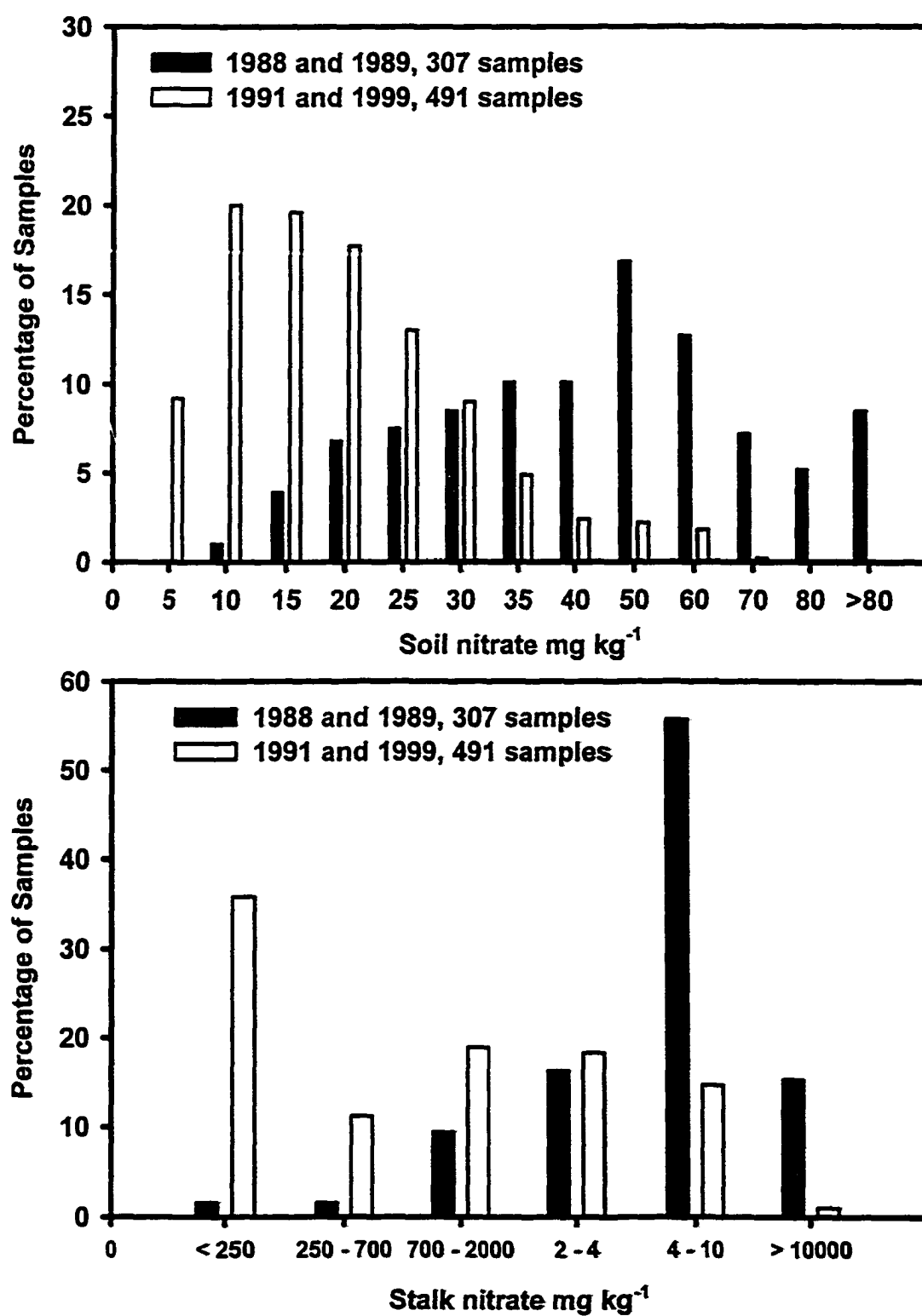


Figure 7. Percentage of soil and stalk nitrate samples within categories from two wet years and two dry years.

# MEASURING THE EFFECTS OF MANURE ON MINERALIZATION OF NITROGEN IN SOILS

A paper prepared for submission to Journal of Environmental Quality

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## **Abstract**

Land application of animal manure alters rates of N mineralization in soils, but quantitative information concerning the intensity and duration of these effects has been difficult to obtain with existing experimental methods. This report describes and demonstrates a new method for obtaining this information. Manure treatments are applied to replicated field plots, and soil samples are periodically collected and analyzed in the laboratory. Analyses include measuring inorganic N present and rates of C and N mineralization under controlled conditions. The potential importance of field treatment effects on N mineralization rates is evaluated through comparisons with background rates of N mineralization and amounts of inorganic N in soils at the time of sampling. Studies showed that effects of liquid swine manure on mineralization rates were important for only a fraction of a growing season in Iowa. The results emphasize the need to distinguish between effects of manure on rates of mineralization in soils and rates at which manure-N is mineralized.

## **Introduction**

Land application of animal manures can supply N for crop growth, but much of the N in manure is organically bound and must be mineralized (i.e., converted to inorganic forms) before it is available to plants. Information concerning rates of this mineralization is needed

to estimate amounts of N a given application will supply to subsequent crops. Estimates of these rates often are given as a decay series, which indicates amounts of N likely to be supplied within various time periods (usually years) after manure is applied. Although decay series often are used in guidelines for animal manure application, quantitative methods for experimentally developing or testing the accuracy of a decay series have never been described. This is a problem because decay series will vary significantly with factors such as methods of manure storage and regional differences in soil temperature and moisture.

Another problem is that additions of organic materials can promote immobilization (i.e., conversion of inorganic to organic forms) of N as well as mineralization of N. Indeed, organic compounds having relatively high C to N ratios tend to stimulate immobilization more than mineralization until the “turning point” occurs, then mineralization is more prevalent than immobilization (Jenkinson, 1981). Although less easy to detect, immobilization also accompanies mineralization when organic compounds having relatively low C to N ratios are decomposed in soils. The processes involved have been discussed in many reviews (Black, 1968; Allison, 1973; Jenkinson, 1981; Jansson and Persson, 1982; Jenkinson et al., 1985; Schepers and Mosier, 1991; Powlson and Barraclough, 1993). Recent studies (Blackmer and Green, 1995; Green and Blackmer, 1995; Green et al., 1995) illustrate the importance of adequately distinguishing between amounts of N mineralized from organic materials and effects of organic materials on *net* amounts of N mineralization within any given period.

The net effects of manure on rates of mineralization in soils can be studied under laboratory conditions by comparing rates of inorganic N accumulation in samples with and without added manure (Flowers and Arnold, 1983; Sims, 1986; Bitzer and Sims, 1988;

Bernal and Kirchmann, 1992). Such studies reveal how rates of mineralization vary with soil conditions and characteristics of manure under controlled conditions. As noted by Flowers and Arnold (1983), however, such studies cannot be expected to give reliable estimates of manure effects on mineralization rates in soils under field conditions, where many factors are continuously changing with time.

Field studies provide important information about effects of manure applications on measurable factors such as soil nitrate concentrations, crop yields, and soil organic matter concentrations (Magdoff, 1978; King, 1984; Klausner et. al., 1994). Such studies do not provide reliable estimates of net effects of manure on N mineralization in soils, however, because effects of mineralization are confounded with effects of several other processes that cannot be controlled under field conditions. These include mineralization of N from organic materials that were in the soil before manure was applied, losses of N from soil by ammonia volatilization, leaching and denitrification, and uptake of N by plants. Additions of manure can affect all of these processes simultaneously, and the magnitude of each effect varies with interactions of manure characteristics and soil conditions. In view of these problems, there is no established experimental method for measuring net effects of manure on mineralization of N in soils under specific field conditions.

The objective of this study is to describe a new experimental approach for estimating net effects of manure on mineralization of N in soils under field conditions. Rather than trying to directly measure effects of manure on mineralization rates in soils, we reasoned that it was more practical to measure the potential importance of these effects at various times after manure is applied. We also reasoned that it is difficult to explain effects of manure on mineralization of N in soils without also observing effects of manure on mineralization of C.

### **Rationale for the New Method**

Studies were initiated with the assumption that the potential importance of manure-induced mineralization at any given time could be measured through laboratory studies that quantify differences in mineralization rates between samples from plots with and without a manure treatment. Large differences in rates would indicate effects of manure were still important, and no detectable differences in rates would indicate that effects were too small to be of practical importance. Measurements on series of samples collected at appropriate times would reveal the temporal pattern in effects of manure on mineralization of N at that site. This series of samples also should reveal how long effects of manure should be considered important amid normal variability in supplies of inorganic N and background rates of N mineralization in soils.

The design of the studies included consideration of various sources of uncertainty normally encountered during land application of animal manures. Major sources of uncertainty are rates of application, percentage of N present in organic forms, nature of organic compounds present, and relationships between time after application and the extent to which organic materials have been decomposed. Under such uncertainty, N management decisions require information about the mean and variability of these effects to determine their importance after manure application.

### **Materials and Methods**

Field trials having replicated plots (15 m long, 4.6 m wide) with and without added manure were established at 6 sites in Iowa between May of 1996 and May of 1998. Three sites were located at the Agronomy and Agricultural Engineering Research Center near Ames, and three were located at the Northern Research and Demonstration Center near



Kanawha. Soils at the sites were mapped as either Clarion (fine-loamy, mixed, superactive, mesic Typic Hapludoll) or Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludoll) loam. Samples collected from the surface 30-cm layer had pH values (1 g soil to 2.5 mL water) ranging from 6.4 to 6.8.

Liquid swine manure was collected from production units typical of those commonly used in Iowa today. This manure included all urine generated by the animals. Manure was continuously added to pits that were emptied once or twice each year, so organic compounds in the manure decomposed under anaerobic conditions for various amounts of time. Manure in the pits was agitated before it was pumped into tanks on land applicators. A sample was collected for laboratory analysis as several tanks were filled, but the sample was not necessarily collected from the tank applied to plots studied in this report.

Two methods of application were compared in a completely randomized design with four replications. One method injected manure to a depth of 5 to 10 cm in bands separated by 30 cm and the other method dribbled manure on the surface in bands without immediate incorporation. Samples of manure applied at each site were collected and analyzed for total N,  $\text{NH}_4\text{-N}$ , and total solids by using methods described by Hach (1988) and APHA (1995), but results of the analysis were not known at the time of application. Concentrations of  $\text{NH}_4\text{-N}$  and organic N in the manure applied, rates and dates of manure application, and sampling times from each site are shown in Table 1. All plots were tilled and managed by practices normally used for corn (*Zea mays* L.) production in Iowa.

Soil samples were collected from each plot to a depth of 30 cm two times after manure application. Samples were not collected on the day of application due to sampling problems caused by water in the manure. The first set of samples was collected from each

plot as soon as soil conditions permitted, but amount of time between application and sampling time varied with weather. The samples were collected 3 to 10 days after application. A second set of samples was collected early in the growing season, usually just before corn needed N to support rapid growth in June, July, and August. The length of time between the first and second sampling times varied depending on whether the manure was applied in Fall or Spring. Time between the first and second samples was 169 days for the site that received manure in the fall and averaged 50 days at sites where manure was applied in the spring.

Each soil sample was derived from a composite of 40 cores (1.7-cm diam) from each plot. The 40 cores were collected in 5 sets of eight cores, where the individual cores in each set were evenly spaced along 30-cm transects that were perpendicular to bands (of manure) and approximately centered on a band. Soil samples were stored at  $-20^{\circ}\text{C}$  until analyses. Soil samples were thawed and sieved (2-mm mesh) in the field-moist condition. Forty-gram portions of each sample were placed in each of 5 flasks having a volume of 1.5 L and a ground-glass joint at the top. The flasks were then sealed with a top consisting of a ground-glass joint and a glass stopcock (1-mm-diam. bore) through which gas samples could be removed. All bottles were placed in an incubator at  $30^{\circ}\text{C}$ . One flask for each soil sample was analyzed after 0, 7, 14, 21, and 28 d of incubation.

Mineralization of C was studied by measuring concentrations of  $\text{CO}_2$  by using a gas chromatograph equipped with an ultrasonic detector, a column system and an injection system as described by Blackmer and Bremner (1977). This method also provided confirmation that  $\text{O}_2$  concentrations in the (relatively large) flasks were essentially unchanged by microbial respiration during incubations. Amounts of C mineralized were

calculated by subtracting amounts of CO<sub>2</sub>-C present in the air of the flasks at the start of the incubation from amounts measured at the end of the incubation.

Mineralization of N during laboratory incubations was studied by measuring accumulations of nitrate and exchangeable ammonium. These were determined by adding 200 mL of 1 N KCl to each flask, shaking the flasks to form a suspension, filtering portions of the suspension and analyzing the filtrate by steam distillation with MgO and Devarda's alloy as described by Keeney and Nelson (1982). The amount of N mineralized during any given incubation was calculated by subtracting the amounts of nitrate and exchangeable ammonium present at the start of the incubation from the amounts found at the end of the incubation. This difference is defined as manure-induced throughout this paper. Rates of N mineralization were calculated by dividing amounts of N mineralized during the incubation by the length of the incubation.

The potential importance of the effect of manure on N mineralization rates in soils was assessed by considering rates of N mineralization in soils not treated with manure and the effects of manure on concentrations of inorganic N in soils when samples were collected. The laboratory studies were assumed to assess only the potential importance of mineralization because an effect observed in the laboratory may not be observed in the field; soil perturbation associated with sampling and mixing, for example, could cause manure-induced mineralization to proceed much more rapidly in the laboratory than it would in the field. Because samples from each plot were analyzed individually in the laboratory, analyses of results of the laboratory studies gave assessments of the importance of treatment effects relative to variability in inorganic N concentrations observed under field conditions.

Data were analyzed by analyses of variance using a general linear model procedure provided by Statistical Analysis System (SAS Inst., 1996). Analyses of variances were computed across sites. Treatment differences were considered significant when  $P > F$  was equal to or less than 0.05. Orthogonal contrast statements were used to further distinguish treatment differences.

## Results

### Composition of the manure applied

Analyses indicated that concentrations of total N in the manure ranged from 2.0 to 6.5 g L<sup>-1</sup> (165 to 249 g N kg<sup>-1</sup> dry matter), and organic N accounted for 14 to 77% of this N (Table 2). These analyses support earlier observations (Hatfield et al., 1998) that liquid swine manure is highly variable in N concentration and percentage of N that is organic. This variability (as well as the fact that N contents were unknown at the time of application) makes it essentially impossible to conduct studies where identical treatments were applied across several sites.

Analyses of data collected showed no useful relationships between calculated amounts of manure-N applied and amounts of manure N recovered in the soil. Apparent recovery of inorganic N measured at the first sampling exceeded 200% for one site and 100% for three sites of the calculated rate of inorganic N supplied by manure application (Table 3). These recoveries are higher if only plots receiving injected applications of manure are considered. Such high recoveries of N usually are not encountered following applications of commercially prepared fertilizers (Binford et al., 1992; Morris et al., 1993), so they must be attributed to difficulties associated with sampling, analyzing, and/or applying manure.

Such problems should be expected because liquid swine manure is a suspension, with organic matter primarily as solids that settle rapidly. Problems caused by variability in manure composition have been described (Sutton, 1992) and they must be expected in research studies conducted under field conditions and in production agriculture. Rapid mineralization of some of the organic N could contribute to the high recoveries observed, but these recoveries of N support the conclusion that exact analysis of manure would not be helpful. Regardless, this observation raises questions concerning the value of analyses that distinguish between these forms of N if it is accepted that our sampling methods were as reliable as those normally used by farmers.

Nitrogen losses before mineralization-immobilization processes occur in soils diminish the importance of knowledge concerning exact amounts and forms of manure-N that leave the manure applicator. Losses of inorganic N by ammonia volatilization during application, for example, could substantially alter the net effects of manure on amounts of N mineralized in soil during any given period. Knowledge of amounts of ammonia volatilized would be of little help because leaching could contribute to some manure-N losses and thereby alter the net effects of manure on amounts of N mineralized in soil during any given period.

### **Mineralization of N**

Mean inorganic N concentrations measured across sites were significant among treatments at the first sampling (Table 3). Mean inorganic N concentrations measured from plots receiving injected applications of manure were significantly greater than plots receiving dribbled applications of manure. Significant treatment effects were also observed for mean inorganic N concentrations measured in the field at the second sampling (Table 3). No

significant differences were observed between injected and dribbled applications of manure at the second sampling. No significant differences were observed among methods of application for the two sample times, but the mean inorganic N concentrations measured on plots that received manure were lower at the second sampling (Table 3). These differences indicate possible losses of N due to leaching, denitrification, ammonia volatilization, or immobilization of N.

Although not significant, higher concentrations of inorganic N found in the soil when manure was injected rather than dribbled on the soil surface suggest possible losses of N by ammonia volatilization soon after application (Table 3). Such differences are expected because it is well established that losses by ammonia volatilization can be substantial when manure is not immediately incorporated into the soil (Hoff et al., 1981). For example, current guidelines for manure management in Iowa suggest that a quarter of the N is lost by ammonia volatilization if liquid manure broadcast on the surface is not incorporated into the soil (Killorn and Lorimor, 1999). Injection of manure into soils can also promote losses of N by denitrification (Comfort et al., 1990).

Manure-induced inorganic N concentrations formed during 28 days of incubation revealed no significant difference between treatments at the first or second sampling (Table 4). No significant difference was detected among methods of application for the two sample times, but manure-induced inorganic N concentrations formed during 28 days of incubation were lower at the second sampling (Table 4). These differences provide additional evidence that immobilization of N may have resulted due to manure applications.

These observations indicate that the sampling methods used were adequate to detect important effects of manure treatments on concentrations of inorganic N in plots. These

findings also indicate that amounts of inorganic N (and possibly some organic N that was mineralized very rapidly) supplied by manure greatly exceeded background levels of inorganic N in soils. The findings are noteworthy because incubations were conducted under ideal conditions; the amounts mineralized under these conditions should be expected to exceed amounts mineralized during the remainder of the growing season under field conditions (Green et al., 1995). These findings indicate, therefore, that potential effects of mineralization of N from the organic fraction of manure usually were much less than observed manure-induced increases of inorganic N concentrations. By the time the first crop started rapid uptake of N, the effects of manure on mineralization rates were less than half the background mineralization rates in soil.

When only means across sites are considered, temporal patterns in N mineralization during laboratory incubations (Fig. 1) showed that manure-induced mineralization of N continued throughout the 28-day incubations (i.e., the lines continued to diverge in Fig. 1). This observation indicates that manure still had detectable effects on mineralization rates under field conditions. If methods with adequate sensitivity were used, the effects probably could be detected for years to come. Such observations, however, do not alter the conclusion that effects of a single manure application on N mineralization rapidly became too small to be of practical importance if other major factors affecting N supplies in soils are not also considered.

Analyses based on means across sites show generally expected trends, but they may also mask important variability among sites. The need to consider variability among sites is shown by the finding that the net effect of manure was to induce immobilization of N at sites 3 and 5 during incubation of soils for the second sampling (Table 4). Such an effect should

be expected if manure contained some material with a relatively high C to N ratio that tended to dominate immobilization-mineralization activities during a period after the immediate effects of manure had been expressed. Undecomposed fragments of feed for swine (e.g., corn grain) should be expected to have high C to N ratios, and decomposition of these materials should be expected to promote net immobilization of N. Because inorganic N can be lost from systems at any time, the net effects of manure on amounts of N mineralized within a given period (i.e., for a given crop) will not vary predictably with analyses that aggregate all forms of organic N into a single category.

### **Mineralization of C**

Temporal patterns in rates of CO<sub>2</sub> release during incubation showed that the effects of manure treatments were small and short-lived in comparison with background rates of CO<sub>2</sub> release from soils (Fig. 2). For the first samples collected after manure application, the mean amounts of CO<sub>2</sub> evolution induced by manure during 28 days of incubation was about one-third the amounts released from non-manured soils during the same period. Essentially all of the effect of manure was expressed during the first 7 days of incubation. Evidence of rapid mineralization of C under field conditions is provided by the finding that the mean effects of manure were equivalent to less than 10% of background levels when the second set of samples were analyzed.

### **Discussion**

The results of this study indicate the need to clearly distinguish among (i) rates at which organic N from manure is mineralized, (ii) net effects of manure on rates of N mineralization in soils, and (iii) net effects of manure on supplies of inorganic N when plants are growing. The rates at which organic N from manure is mineralized must always be



positive and should be expected to gradually decrease with time. Commonly used decay series (Pratt et al., 1973 and 1976) seem to follow such a pattern, but methods used to calculate decay rates have never been explained. It is essentially impossible to measure rates at which organic N is mineralized in soils, and information concerning these rates has little practical value.

The net effects of manure on mineralization, however, can be much more complex and vary with nature of organic compounds in manure. The net effects of manure on rates of mineralization can be either negative or positive during any given time during decomposition of manure. The net effect of manure on mineralization, therefore, can be to either decrease or increase supplies of inorganic N for growth of a given crop. Although the net effects on mineralization may follow a predictable pattern with respect to percentage decomposition of manure, percentage decomposition at any given time varies with site conditions and is essentially unknown under field conditions. The proposed method has value because it can measure net effects of manure on mineralization of N during any given period (i.e., for a specific crop grown after the manure is applied).

The measurements were made across a range of conditions selected to be representative of those found when liquid swine manure is applied for corn production in Iowa. Exact information concerning rates of organic N application was not needed because exact rates of application usually are not known in production agriculture and because percentage decomposition of organic N is never known with certainty under field conditions. Under such conditions, knowledge of the range of effects normally observed under field conditions is all that is needed to make informed management decisions.

Liquid swine manure effects on inorganic N supplies for plant growth were much more important than manure effects on mineralization rates. This finding can be explained by recognizing that substantial portions of N in manure were present as ammonium and those organic compounds most susceptible to microbial degradation probably degraded during storage in the pit. Liquid swine manure essentially had an inorganic fraction that behaves like a commercial fertilizer and an organic fraction that is relatively inert. Liquid swine manure, therefore, differs greatly from fresh or composted manures, which would produce net effects on mineralization nearly equal to net effects on supplies of inorganic N in soils. The new method can provide information needed to make appropriate distinctions between various types of animal manure.

The results of this study should not be considered evidence that cumulative effects of many applications of liquid swine manure are unimportant. Abundant evidence suggests that much of the C and N in organic materials added to soils remains for years and slightly increases rates of mineralization of soils. The proposed method could be used to measure cumulative net effects of successive applications of liquid swine manure on N mineralization rates in soils. It needs to be recognized, however, that for annual crops like corn it may be more practical and informative to simply measure net effects of these applications on concentrations of inorganic N in soil when crops begin N uptake to support crop growth.

### Conclusions

The *net* effects of animal manure on N mineralization in soils during any period (i.e., for any given crop) can be measured by laboratory analyses of soil samples collected from field plots with and without added manure. Rates of N mineralization observed under laboratory conditions reveal differences due to manure treatments applied in the field. The

potential importance of these differences can be evaluated through comparisons with background rates of mineralization and effects of manure on concentrations of inorganic N under field conditions. Simultaneous measurements of C mineralization rates help explain observed differences by using existing knowledge about the effects of carbonaceous materials on N transformations in soils.

Although these studies were intended to learn about measuring net effects of manure on mineralization of N in soils, the results clearly illustrate the importance of methods that can measure the net effect of manure on supplies of inorganic N present when plants grow. Results presented here and elsewhere suggest that soil testing for nitrate early in the growing season can be used for this purpose. In regard to the need for the studies reported here, however, such soil tests are not likely to be accepted in situations where manure is believed to induce large amounts of mineralization after soils are sampled.

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Table 1. Rates and dates of manure application for 6 sites and dates soil samples were collected.

Site	Date of application	Rate of application	First sampling	Second sampling
		--ML ha <sup>-1</sup> --		
1 (K)†	5-5-98	38	5-8-98	6-22-98
2 (K)	5-6-96	17	5-16-96	6-27-96
3 (A)	10-30-97	57	11-5-97	4-23-98
4 (K)	4-24-97	19	5-2-97	6-5-97
5 (A)	4-15-97	46	4-18-97	6-5-97
6 (A)	4-22-98	68	4-24-98	7-16-98

† Kanawha or Ames location.

Table 2. Results of analysis of liquid swine manure applied at 6 sites.

Site	Amounts applied		
	Total solids	NH <sub>4</sub> -N	Organic-N
		kg ha <sup>-1</sup>	
1	1493	57	189
2	850	28	41
3	913	105	45
4	188	33	11
5	448	69	23
6	571	122	20

Table 3. Concentrations of inorganic N measured in the field at two sampling times

Site	Treatment	Inorganic N measured in the field			
		First sampling		Second sampling	
		Mean mg N kg <sup>-1</sup>	CV %	Mean mg N kg <sup>-1</sup>	CV %
1	Control	3.6	12	6.0	15
	Dribbled	31.9	11	28.6	5
	Injected	34.1	16	35.9	11
2	Control	8.3	29	7.9	27
	Dribbled	19.2	18	18.2	18
	Injected	21.6	40	20.3	39
3	Control	4.7	55	3.1	29
	Dribbled	16.0	38	7.2	31
	Injected	42.3	52	20.0	50
4	Control	5.1	18	8.4	23
	Dribbled	14.8	30	33.5	30
	Injected	16.6	15	32.0	26
5	Control	7.4	0.3	8.0	15
	Dribbled	20.5	40	14.5	12
	Injected	34.7	36	27.5	15
6	Control	4.3	26	3.7	30
	Dribbled	16.2	41	3.9	26
	Injected	25.7	23	6.9	35
Mean	Control	5.6	33	6.2	37
	Dribbled	19.7	32	17.7	66
	Injected	29.2	33	23.8	44



Table 4. Amounts of inorganic N formed during incubation of samples collected at two times.

Site	Treatment	Inorganic N formed during 28 days of incubation			
		First sampling		Second sampling	
		Mean	CV	Mean	CV
		mg N kg <sup>-1</sup>	%	mg N kg <sup>-1</sup>	%
1	Control	5.4	12	9.5	7
	Dribbled	10.4	27	15.2	12
	Injected	10.3	58	14.4	5
2	Control	19.8	25	13.9	32
	Dribbled	37.7	41	20.4	14
	Injected	57.7	37	21.5	17
3	Control	14.7	34	9.1	22
	Dribbled	24.7	33	9.3	15
	Injected	30.7	47	8.5	45
4	Control	12.8	4	12.2	7
	Dribbled	26.0	27	20.7	22
	Injected	23.8	41	25.5	72
5	Control	17.3	17	14.6	12
	Dribbled	16.4	23	13.8	6
	Injected	13.7	37	12.5	25
6	Control	17.8	26	12.6	10
	Dribbled	18.7	10	12.0	24
	Injected	16.3	18	12.2	21
Mean	Control	14.6	35	12.0	19
	Dribbled	22.1	43	15.2	30
	Injected	25.4	69	15.8	41

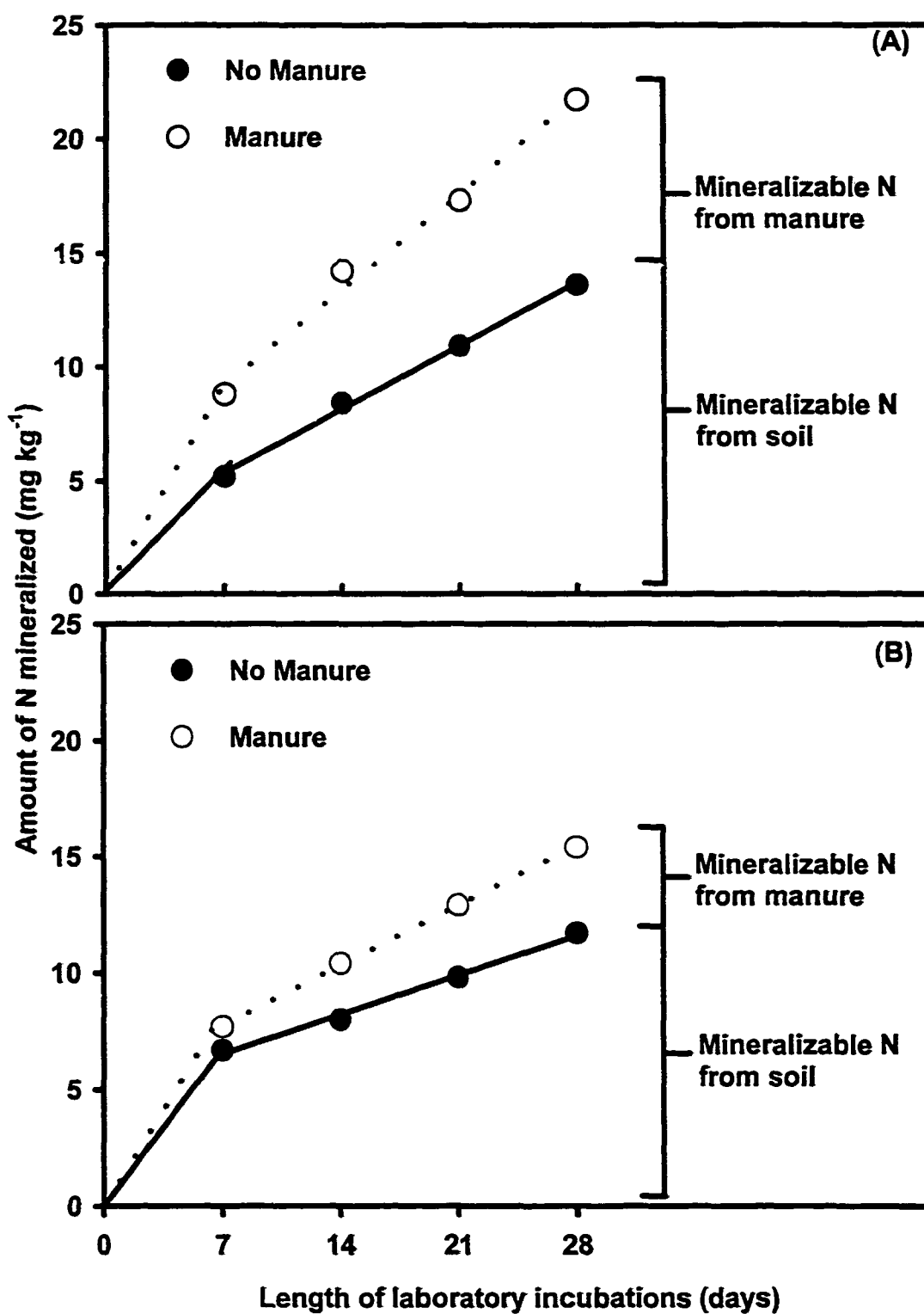


Figure 1. Amounts of N mineralized (mg N kg<sup>-1</sup> soil) from soils incubated with and without manure from the first (A) and second (B) sampling times.

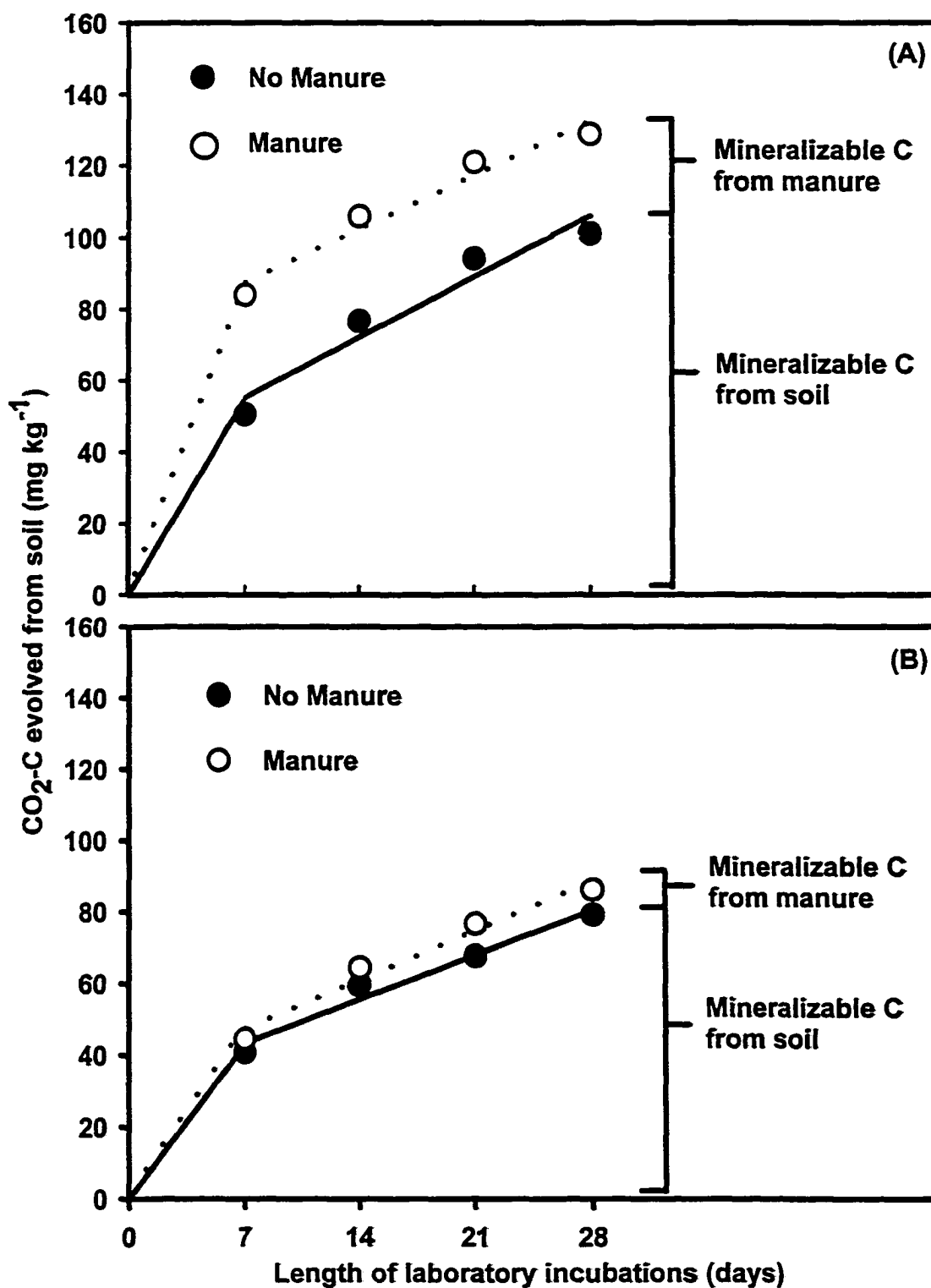


Figure 2. Amounts of C mineralized ( $\text{mg C kg}^{-1}$  soil) from soils incubated with and without manure from the first (A) and second (B) sampling time.

## TIME AND METHOD OF SPRING NITROGEN APPLICATIONS TO CORRECT DEFICIENCIES IN CORN

A paper prepared for submission to Agronomy Journal

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### Abstract

The ability to detect nitrogen (N) deficiencies in corn (*Zea mays* L.) after fall-applied N applications has improved with precision farming technologies and research is required to address fertilizer practices that can correct these deficiencies. This study was conducted to examine the effects of time and method of spring N applications on yield, grain protein concentrations, and canopy reflectance values after fall-applied N applications. In 1999, three field-scale sites fertilized in fall of 1998 received 112 kg N ha<sup>-1</sup> as urea-ammonium nitrate solution (UAN) at two times after planting. Two application methods were compared at two times to plots that received no additional N in a split-plot design. One application method consisted of surface banding (dribbled) and the other consisted of injected banding (injected). Yield difference was significant at two of the three sites, while grain protein concentrations and canopy reflectance value differences were significant across all three sites. No differences were detected between times of application or dribbled and injected applications. These results confirm deficiencies of fall-applied N and demonstrated dribbled or injected N applications were effective in correcting these deficiencies from shortly after planting until prior to clearance of normal side-dress equipment over the corn canopy.

## Introduction

Anhydrous ammonia accounts for the highest percentage of fertilizer tonnage sales in the West North Central states (Berry, 1992). Fall applications of anhydrous ammonia offer advantages to farmers and dealers (Stehouwer and Johnson, 1990). These advantages include less time constraints associated with application and alleviation of supply and demand conflicts. However, potential losses of nitrate associated with denitrification and leaching are greater compared to spring applications (Stehouwer and Johnson, 1990; Bundy et al., 1992). Losses of N represent an economic loss as well as a threat to ground and surface water supplies. Recently, N loading of the Mississippi River associated with losses from the agricultural landscape has been one cause attributed to the hypoxic zone in the Gulf of Mexico (Downing et al., 1999).

The advent of precision farming technologies (global positioning systems GPS, geographic information systems GIS, yield monitors, and remote sensing) enhances the ability to detect N losses and distinguish areas of fields where losses may occur. Blackmer and White (1998) describe how these tools could be used to assist in improving N recommendations on a field-scale basis. More recent studies using these technologies have demonstrated that potential for losses of fall-applied N soon after application still exists (White and Blackmer, 1997; Blackmer and Ellsworth, 2000; Ellsworth and Blackmer, 2000). Blackmer et al., (2000) conducted intensive sampling within and between bands left by anhydrous applicators and found a relationship between percent recovery of N as exchangeable ammonium and nitrate and soil pH. Remote sensing utilized by Ellsworth and Blackmer (2000) revealed areas of N deficiencies that corresponded to areas of high soil pH.

Evidence indicating that losses of fall-applied N can occur and may be more prone on areas of high soil pH identifies a need for research that addresses N management practices to correct N deficiencies after they occur. Additional N applications to correct deficiencies require management decisions involving time and method of application. Primarily, research that addresses time and method of N application questions has focused on increasing UAN efficiency in no-till corn (Touchton and Hargrove, 1982; Fox et al., 1986; Howard and Tyler, 1989; Stecker et al., 1993). These studies evaluated N applications at planting and later to determine which combination of times and methods resulted in higher efficiencies of N (i.e. less losses of N). However, these studies focus on eliminating the potential for possible deficiencies as opposed to correcting deficiencies after they occur.

Timing N applications to coincide with periods of rapid uptake decrease risk associated with leaching and denitrification because plants can utilize applied N more efficiently before substantial losses occur (Olson and Kurtz, 1982), therefore additional N applications at this time should help alleviate deficiencies. Studies examining application methods of UAN solutions in no-till corn have shown that injected applications produce superior yields over broadcast surface applications because ammonia volatilization losses are minimized (Mengel et al., 1982; Touchton and Hargrove, 1982). Surface banded (dribbled) solutions have also been shown to produce higher yields than broadcast applications (Touchton and Hargrove, 1982; Fox and Piekielek, 1987). However, other studies have observed no difference between dribbled and broadcast UAN applications (Howard and Tyler, 1989; Stecker et al., 1993).

Research related to management practices such as time and method of spring N applications can help alleviate deficiencies and lost profits. However, limited research is

available that assess time and method of UAN applications in corn production to correct N deficiencies after applications of fall-applied N. The advent of precision farming technologies provides the capacity to evaluate these effects in field-scale studies. The objective of this paper was to evaluate the effects of time and method of spring UAN applications on yield, grain protein concentrations, and canopy reflectance values after fall-applied N applications.

### Materials and Methods

Three precision farming strip-plot trials were conducted in Greene County, Iowa, in 1999 where anhydrous ammonia ( $125$  to  $130$  kg N ha<sup>-1</sup>) had been applied in the fall of 1998. Each site was planted to corn following soybean (*Glycine max* L). Two of the three sites were conducted in no-till fields established for at least 7 yr. The farmers conducted all management practices as normal, except for spring N fertilization.

Fertilizer treatments consisted of no extra N or  $112$  kg N ha<sup>-1</sup> applied in 8-row (Site 1) or 6-row (Site 2 and 3) strips extending the length of the field. Extra N (32% UAN) was applied by two methods (dribbled and injected) at two times in a split-plot design with five (Site 1 and 2) and three (Site 3) replications. The two times for additional N fertilizer applications were on May 26 and June 21 for site 1, May 25 and June 14 for site 2, and May 29 and June 14 for site 3. Whole plot was time and method of application was the split plot. Dribbled fertilizer was placed between the rows and involved no incorporation, while injected fertilizer was placed between the rows 15 to 20 cm below the soil surface. Plots not receiving fertilizer were included to determine the response to additional N.

Soil samples were collected from fifteen “test areas” located within each site. Locations of the test areas were chosen to represent the widest range in soil characteristics.

The location of the test areas within each site as well as the boundaries of soil mapping units and treatment strips for each site are shown in Fig. 1, 2, and 3. The corresponding soil type associated with each map unit and its percentage of area covered within each site are listed in Table 1. Test areas were 6 m long and the width of a strip in an area of seemingly uniform soil. The small dimensions of the test areas represent point samples across each site.

Soil samples were only collected from control strips because some fertilizer treatments had already been applied in other strips as a result of the time of application associated with additional N. Soil samples were collected when corn was 15-30 cm in height. A composite sample was obtained for each test area, consisting of thirty-two 30 cm x 1.2 cm (dia.) cores. Soil samples were ground to pass a 2 mm sieve, extracted in 2 M KCl with a 1:5 soil:extractant ratio, shaken for 30 min, and filtered. The filtrates were analyzed for nitrate and exchangeable ammonium by steam distillation described by Keeney and Nelson (1982). Phosphorus (P), potassium (K), pH, and organic matter (O.M.) were also obtained on samples from each test area using procedures recommended for the North Central Region (North Central Regional Research Publication No. 221, 1998). Briefly, P was determined with the Bray P1 extractant, K was determined with ammonium acetate, pH was measured in a 1:1 ratio of soil and water by volume, and O.M. was measured by the Walkley-Black procedure. The results of these analyses as well as exchangeable ammonium are presented in Table 2.

Color aerial images were taken at each site two times near the end of the growing season. Images of the canopy were taken 6 and 26 August by Aerial Services, Inc. (Cedar Falls, IA) with a Jena LMK model 1000 (152mm) Precision Lens Aerial Camera System with Forward Image Motion Compensation mounted on a gyro-stabilizer in an airplane.



Each image was digitized using a Hewlett-Packard Scanjet 6100c scanner and geo-referenced in Arcview 3.2 (ESRI) using Image Analyst 1.0. Mean canopy reflectance values from the green band were obtained within each strip. Relative reflectance values were defined as mean canopy reflectance values of each strip within each block expressed as a percentage of the mean canopy reflectance values measured from the injected treatment strip applied at the second time within the corresponding block. This procedure puts all canopy reflectance values relative to the injected treatment applied at the second time. Control points used for geo-referencing were 60 cm x 120 cm plywood targets painted white and placed in the field at the corners of the study area. Corn was cleared 3 m from the center of the targets to ensure visibility throughout the season.

End of season cornstalk samples were collected 1-3 wk after black layers had formed at the base of most kernels. Fifteen stalks were collected from the center two rows of each treatment within the fifteen test areas by cutting a 20 cm segment of stalk beginning 15 cm above the ground. Cornstalks were dried in a forced-air dryer at 60°C and ground to pass a 0.5 mm sieve. Cornstalk samples were extracted in 0.5 M KCl with a 1:50 tissue:extractant ratio, shaken for 30 min, and filtered. Nitrate determinations were obtained for the filtrates using identical steam distillation procedures used for the soil samples.

Combines equipped with yield monitors and global positioning systems (GPS) were used to measure corn yields. Yields were recorded at one-second intervals and adjusted to 155 g kg<sup>-1</sup> moisture content. The yield files were then exported to Arcview for analysis. Samples of grain were collected from each treatment strip using a 1.5 m grain probe (Seedburo Equipment, Co.), and analyzed for protein concentration using established NIR

techniques at the Iowa Grain Quality Laboratory. Protein concentrations were reported at a moisture content of 155 g kg<sup>-1</sup>.

Data were analyzed by analyses of variance using general linear model procedure provided by the Statistical Analysis System (SAS Inst., 1996). Calculated LSD was used to separate means when the F-test was significant ( $P < 0.05$ ). Orthogonal contrast statements were used to further divide differences between methods of application.

## **Results**

### **Data from test areas**

Soil nitrate concentrations found at the fifteen test areas, within each field, were less than the 20 to 25 mg N kg<sup>-1</sup>, which is normally considered optimal for corn growth (Blackmer et al., 1989; Bundy and Meisinger, 1994) (Table 3). The samples indicated that a substantial portion of each field had concentrations of nitrate less than 10 mg N kg<sup>-1</sup>. Variability in nitrate concentrations should be expected because the fifteen test areas were selected to include extremes in soil conditions within each field. The variability in soil nitrate concentrations was similar to variability observed in soil test values for P and K. Nitrification of the fertilizer was essentially complete because concentrations of exchangeable ammonium averaged less than 3 mg N kg<sup>-1</sup> (Table 2).

Concentrations of nitrate in cornstalks measured at the end of the season indicated severe deficiencies of N where additional N fertilizer was not applied (Table 4). Mean concentrations at two of the sites were in the optimal range, but means of stalk nitrate concentrations can hide deficiencies that occur in parts of the field. This problem can be minimized by considering the percentage of test areas within each of the stalk nitrate categories. Such analyses show that the majority of samples collected within each field fell

within the low category. The results of stalk testing in the fall showed good agreement with results obtained by soil testing in the spring.

#### **Data from whole-field analyses**

Application of additional N significantly increased yields at two of the sites (Table 5). Neither time nor method of application had significant effects on yields obtained at each site. Perfect agreement between results of whole-field analyses and results from test areas should not be expected because test areas were selected to capture the widest possible range of soil characteristics within the field rather than to estimate means for soil characteristics in the field.

Concentrations of protein in grain were significantly increased by application of additional N fertilizer at all three sites (Table 6). These increases indicate that the addition of N corrected N deficiencies in each field. The finding that grain protein concentrations were increased at site 1 even though yields were not can be explained by observations of Cerrato and Blackmer (1990), who observed that grain protein concentrations tended to maximize at slightly higher rates of fertilization than do yields. The finding that grain protein concentrations increased at site 1 indicates that supplies of N were barely adequate to maximize yields. Neither time nor method of application had significant effects on grain protein concentrations.

Digital analysis conducted on canopy reflectance values from aerial images taken on 6 and 27 August showed significant effects to additional N (Table 7). Correction of N deficiencies decrease canopy reflectance values, so relative reflectance values significantly greater than values of 1.000 or less indicates deficiencies (Table 7). Relative reflectance values less than 1.000 indicate the injected treatment applied at the second time did not

always result in the lowest reflectance values measured for each site. Significant effects observed at site 1 suggest that measurements of canopy reflectance are more sensitive than yield measurements for detecting borderline deficiencies of N in the crop. Information attained by digital analysis can be qualitatively verified by visual examination of the images (lighter green color indicates higher reflectance) (Fig. 1, 2, and 3).

The image taken at site 3 showed areas of high and low reflectance that seemed to correspond to soil mapping units (Fig. 3). High reflectance tended to occur on calcareous soils. Regression analysis indicated that soil pH explained 53 % of the variability in soil nitrate concentrations at this site (data not shown). Lower concentrations of nitrate were found at high pH, a finding that suggests that losses of fall-applied N were greater on high pH soils. Analyses that partitioned the field into calcareous and non-calcareous areas revealed that responses to N fertilizer were greater on the calcareous than on the non-calcareous soils (Table 8 and 9). These observations support the findings of Ellsworth and Blackmer (2000) and Blackmer et al. (2000). Neither time nor method of application had a significant effect in either the calcareous or non-calcareous soils.

### **Discussion**

Soil nitrate concentrations measured from fifteen test areas in the spring indicated that yield-limiting deficiencies should be expected without additional N fertilizer applications for all three sites (Blackmer et al., 1997). Stalk nitrate concentrations measured from the fifteen test areas in the fall confirmed results measured in the spring and suggest that N was not present in the rooting zone as opposed to not in the top 30 cm of soil. Yield data collected from two of the three sites demonstrated significant yield increases to additional N fertilization. These results were validated by canopy reflectance values and grain protein

concentrations. Canopy reflectance values and grain protein concentrations appeared to be more sensitive than yield measurements for detecting treatment differences. This finding was illustrated at site 1, where yields were not significant, but canopy reflectance values and grain protein concentrations indicated significant responses to additional N.

Site 3 revealed spatial patterns of N response throughout the field. The significant yield response observed on calcareous soils indicated that nitrate concentrations were likely lower than nitrate concentrations found on non-calcareous soils suggesting that losses were greater on calcareous soils. Identifying calcareous areas within fields prior to N fertilization improves N management by avoiding unnecessary N applications that are subject to being lost prior to crop utilization. Nitrogen applications to fields with significant portions of high soil pH areas should be delayed until just prior to rapid uptake by plants, therefore, decreasing the potential for losses and increasing N efficiency.

Time of application was not significant for yields, grain protein concentrations, or canopy reflectance values. No difference between times of application is a significant finding. Producers complain that spring N applications may be hampered by wet soils, which may be prone to compaction, and they don't want to risk not being able to apply N due to these conditions. Another concern is an intense workload during spring competes for time required to apply N. Nitrogen applications that are delayed prior to clearance of normal side-dress equipment over the corn canopy address these concerns by allowing the window of application to be expanded and simultaneously decreasing risk associated with N losses preceding uptake.

No significant difference was measured between dribbled and injected methods of application for yield, grain protein concentrations, or canopy reflectance values. The

implications of this finding illustrate advantages of dribbled applications compared to injected and fall-applied N applications. Dribbled applications can be applied faster than injected applications, which alleviate time constraints farmers are faced with due to intense workloads during the spring. Dribbled applications are also cheaper to apply than injected applications (Roberts et al., 1995) and can be cheaper than fall-applied N because less N may be required in the spring due to increased N efficiency.

Rainfall events occurred frequently during the times of additional N application at all sites in 1999. Fox et al. (1986) related apparent ammonia volatilization losses from surface banded UAN to the number of days after application until a total of 10 mm of rain fell. Losses increased as the number of days increased until 10 mm of rain fell. Raun et al. (1989) found higher corn yields when surface broadcast UAN applications were followed by sprinkler irrigation compared to surface banded or injected band UAN applications in a ridge-till system. Rainfall following applications of dribbled UAN in our study probably helped to minimize N losses attributable to ammonia volatilization from this treatment.

### **Conclusions**

Nitrogen deficiencies after fall-applied N were detectable with yields, grain protein concentrations, and canopy reflectance values. Yield responses were measured after additional N applications for two of the three sites, while grain protein concentrations and canopy reflectance values indicated N responses at all three sites. No significant differences were observed for time of application or between dribbled and injected treatments for yield, grain protein concentrations, or canopy reflectance values at any site. The response to additional N after applications of fall-applied N implies that fall N rates were not high enough to maximize yields or losses of fall-applied N occurred before rapid uptake of N

began. Based on data collected in this study, only responses to additional N can be confirmed.

These studies demonstrate how precision farming technologies can be utilized in field-scale studies to make comparisons between fall-applied N and side-dress applications. This technology demonstrates how these comparisons can help producers determine N applications that result in the least risk, while alleviating N losses to surface and groundwater supplies.

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Table 1. Distribution of soil map units for three strip-plot trials in 1999.

Site	Map Unit	Soil Name	Family Name	% area of trial
1	6	Okoboji	Fine, smectitic, mesic Cumulic Vertic Endoaquolls	0.3
	55	Nicollet	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls	4.8
	107	Webster	Fine-loamy, mixed, superactive, mesic Typic Haplaquolls	17.1
	138B	Clarion	Fine-loamy, mixed, superactive, mesic Typic Hapludolls	44.7
	138B2	Clarion	Fine-loamy, mixed, superactive, mesic Typic Hapludolls	1.7
	138C2	Clarion	Fine-loamy, mixed, superactive, mesic Typic Hapludolls	22.4
	507	Canisteo	Fine-loamy, mixed, superactive, calcareous, mesic Typic Haplaquolls	7.6
	638D2	Clarion-Storden loam†	Fine-loamy, mixed, superactive, mesic Typic Hapludolls Fine-loamy, mixed, superactive, mesic Typic Eutrudepts	1.4
2	6	Okoboji	Fine, smectitic, mesic Cumulic Vertic Endoaquolls	0.2
	55	Nicollet	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls	31.9
	107	Webster	Fine-loamy, mixed, superactive, mesic Typic Haplaquolls	19.9
	138B	Clarion	Fine-loamy, mixed, superactive, mesic Typic Hapludolls	17.9
	138B2	Clarion	Fine-loamy, mixed, superactive, mesic Typic Hapludolls	5.5
	138C2	Clarion	Fine-loamy, mixed, superactive, mesic Typic Hapludolls	0.9
	236B2	Lester	Fine-loamy, mixed, superactive, mesic Mollic Hapludalfs	21.4
	325	Le Sueur	Fine-loamy, mixed, superactive, mesic Aquic Argiudolls	0.5
3	878B	Ocheyedan	Fine-loamy, mixed, mesic Typic Hapludolls	2.0
	55	Nicollet	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls	0.1
	135	Coland		18.3
	138B2	Clarion	Fine-loamy, mixed, superactive, mesic Typic Hapludolls	16.5
	138C2	Clarion	Fine-loamy, mixed, superactive, mesic Typic Hapludolls	1.5
		Coland	Fine-loamy, mixed, superactive, mesic Cumulic Endoaquolls	
	585B	Spillville complex†	Fine-loamy, mixed, superactive, mesic Cumulic Hapludolls	24.6
	638C2	Clarion-Storden loam†	Fine-loamy, mixed, superactive, mesic Typic Hapludolls Fine-loamy, mixed, superactive, mesic Typic Eutrudepts	25.6
	638D2	Clarion-Storden loam†	Fine-loamy, mixed, superactive, mesic Typic Hapludolls Fine-loamy, mixed, superactive, mesic Typic Eutrudepts	13.4

† Family names correspond to adjacent soil names.

Table 2. Mean, standard deviation, range, and coefficient of variation for selected soil characteristics from 15 test areas within 3 fields.

Site		P	K	pH	O.M	NH <sub>4</sub> -N
		-----mg kg <sup>-1</sup> -----			-----%-----	---mg kg <sup>-1</sup> ---
1	Mean	27	146	6.2	3.2	6
	SD	22	83	0.4	0.9	2
	Range	11 - 96	97 - 433	5.6 - 7.2	2.2 - 5.3	3 - 10
	CV†	82	57	7	27	40
2	Mean	23	151	6.0	3.8	6
	SD	13	23	0.4	0.5	3
	Range	10 - 51	121 - 201	5.4 - 6.8	2.8 - 4.7	3 - 11
	CV	56	15	6	14	42
3	Mean	21	136	6.4	4.2	4
	SD	21	68	0.9	1.8	2
	Range	1 - 66	67 - 259	5.4 - 8.2	2.2 - 7.8	2 - 8
	CV	98	50	14	43	54

† Coefficient of variation in %.

Table 3. Mean, standard deviations, range, and coefficient of variations and distribution of soil nitrate concentrations from 15 test areas measured within 3 sites in 1999.

Site	Mean	SD	Range	CV	Percentage within categories†			
					Low	Marginal	Optimal	High
	-----mg N kg <sup>-1</sup> -----				-----%-----			
1	8	5	3-25	69	79	14	7	0
2	6	3	3-11	42	87	13	0	0
3	4	2	2-8	54	100	0	0	0

† Low (<10 mg N kg<sup>-1</sup>), marginal (10-19 mg N kg<sup>-1</sup>), optimal (20-29 mg N kg<sup>-1</sup>), and high (>29 mg N kg<sup>-1</sup> ppm).

Table 4. Stalk nitrate concentrations measured at fifteen test areas for three sites in 1999.

Site	Time of application	Method of application	Mean	Range	CV	Percentage within categories†		
						Low	Optimal	High
			-----mg N kg <sup>-1</sup> -----	-----%-----				
1	1	Control	522‡	36 - 2032	115	53	40	7
		Dribbled	2643	34 - 4988	56	7	33	60
		Injected	2631	947 - 5146	39	0	27	27
	2	Dribbled	3497	995 - 6477	37	0	7	93
		Injected	2564	1649 - 3642	24	0	20	80
	2	1	Control	608	12 - 2314	145	60	27
Dribbled			418	18 - 1203	87	33	67	0
Injected			1074	59 - 3275	83	27	60	13
2		Dribbled	1048	13 - 1917	51	7	93	0
		Injected	681	106 - 1624	66	20	80	0
3		1	Control	186	7 - 1066	152	93	7
	Dribbled		2108	139 - 5348	76	13	33	53
	Injected		1853	149 - 3663	69	13	40	47
	2	Dribbled	1099	123 - 3606	92	20	67	13
		Injected	1886	216 - 5348	77	7	53	40

† Low (<250 mg N kg<sup>-1</sup>), optimal (250-2000 mg N kg<sup>-1</sup>), and high (>2000 mg N kg<sup>-1</sup>)

‡ Stalk nitrate categories; Low (< 250 mg N kg<sup>-1</sup>) indicates high probability that additional N would have resulted in higher yields, Optimal (700 to 2000 mg N kg<sup>-1</sup>) indicates high probability that N was within range to maximize profits, High (> 2000 mg N kg<sup>-1</sup>) indicates high probability that N exceeded requirements resulting in decreased profits.

Table 5. Time and method of application effects on yields for 3 sites in 1999.

Table 3. Time and method of application effects on yields for 3 sites in 1977.					
Site	Time of Application†	Yield			Mean
		Control	Dribbled	Injected	
Mg ha <sup>-1</sup>					
1	1	11.08	11.13	11.18	11.13
	2	11.15	11.28	11.36	11.26
	Mean	11.12	11.21	11.27	11.20
2	1	8.40	9.87	9.48	9.25
	2	8.40	9.52	9.80	9.24
	Mean‡	8.40	9.70	9.64	9.25
3	1	8.76	9.41	9.44	9.20
	2	8.45	9.47	9.46	9.13
	Mean	8.61	9.44	9.45	9.17

† No significant difference between times of application was observed for any site.

‡ LSD for method of application means are 0.38 and 0.71 Mg ha<sup>-1</sup> for site 2 and 3, respectively. Site 1 was non-responsive.

Table 6. Time and method of application effects of grain protein concentrations measured for 3 sites in 1999.

Site	Time of application†	Protein			Mean
		Control	Dribbled	Injected	
		g kg <sup>-1</sup>			
1	1	68.2	71.4	71.8	70.5
	2	67.0	72.0	72.4	70.5
	Mean‡	67.6	71.7	72.1	
2	1	67.2	76.8	78.2	74.1
	2	65.6	77.4	78.2	73.7
	Mean	66.4	77.1	78.2	
3	1	60.3	63.6	63.0	62.3
	2	56.7	61.6	66.0	61.4
	Mean	58.5	62.6	64.5	

† No significant difference between times of application was observed for any site.

‡ LSD for method of application means are 1.9, 1.5, and 2.4 g kg<sup>-1</sup> for site 1, 2, and 3, respectively.

Table 7. Time and method of application effects of relative green band reflectance values measured on two different image dates for three sites in 1999.

Site	Time of application	Relative green band reflectance values for two image dates							
		8-06-99				8-27-99			
		Control	Dribbled	Injected	Mean†	Control	Dribbled	Injected	Mean
1	1	1.038	1.016	0.999	1.018	1.042	1.019	1.007	1.023
	2	1.025	0.992	1.000	1.006	1.036	1.001	1.000	1.012
	Mean‡	1.032	1.004	1.000		1.039	1.010	1.004	
2	1	1.197	1.012	1.013	1.074	1.151	1.034	1.001	1.062
	2	1.205	1.009	1.000	1.071	1.156	1.007	1.000	1.054
	Mean	1.201	1.011	1.007		1.154	1.021	1.001	
3	1	1.104	0.927	0.927	0.986	1.079	0.983	1.004	1.022
	2	1.137	0.973	1.000	1.037	1.094	1.008	1.000	1.034
	Mean	1.121	0.950	0.964		1.087	0.996	1.002	

† No significant difference between times of application was observed for any sites across the two dates images were taken.

‡ LSD for method of application means within the early date are 0.011, 0.053, and 0.058 for site 1, 2, and 3, respectively. LSD for method of application means within the later date are 0.008, 0.022, and 0.035 for site 1, 2, and 3, respectively.

Table 8. Time and method of applications effects of yields measured on soils mapped as calcareous and non-calcareous within site 3 in 1999.

Time of Application†	Yield							
	Calcareous				Non-calcareous			
	Control	Dribbled	Injected	Mean	Control	Dribbled	Injected	Mean
	Mg ha <sup>-1</sup>				Mg ha <sup>-1</sup>			
1	7.16	8.39	8.57	8.04	9.80	10.13	10.04	9.99
2	6.92	8.38	8.34	7.88	9.43	10.29	10.26	9.99
Mean‡	7.04	8.39	8.46	7.96	9.62	10.21	10.15	9.99

† No significant difference was observed for time of application on soils mapped as calcareous or non-calcareous.

‡ LSD for method of application means within calcareous soils is 0.82 Mg ha<sup>-1</sup>. Method of application was not significant for non-calcareous soils.

Table 9. Time and method of application effects of relative green band reflectance values for two image dates measured on soils mapped as calcareous and non-calcareous within site 3 in 1999.

Image date	Application time	Calcareous				Non-calcareous			
		C†	D	I	Mean‡	C	D	I	Mean
8-06-99	1	1.154	0.968	0.866	0.996	1.077	0.937	0.926	0.980
	2	1.179	0.939	1.000	1.039	1.116	0.993	1.000	1.036
	Mean§	1.167	0.954	0.933		1.097	0.965	0.963	
8-27-99	1	1.116	1.006	0.976	1.033	1.059	1.002	0.986	1.016
	2	1.122	1.015	1.000	1.046	1.082	1.005	1.000	1.029
	Mean¶	1.119	1.011	0.988		1.071	1.004	0.993	

† C, D, and I correspond to control, dribbled, and injected treatments.

‡ No significant difference was observed for time of application on soils mapped as calcareous or non-calcareous.

§ LSD for method of application means within calcareous soils is 0.053 and within non-calcareous soils is 0.040.

¶ LSD for method of application means within calcareous soils is 0.080 and within non-calcareous soils is 0.039.



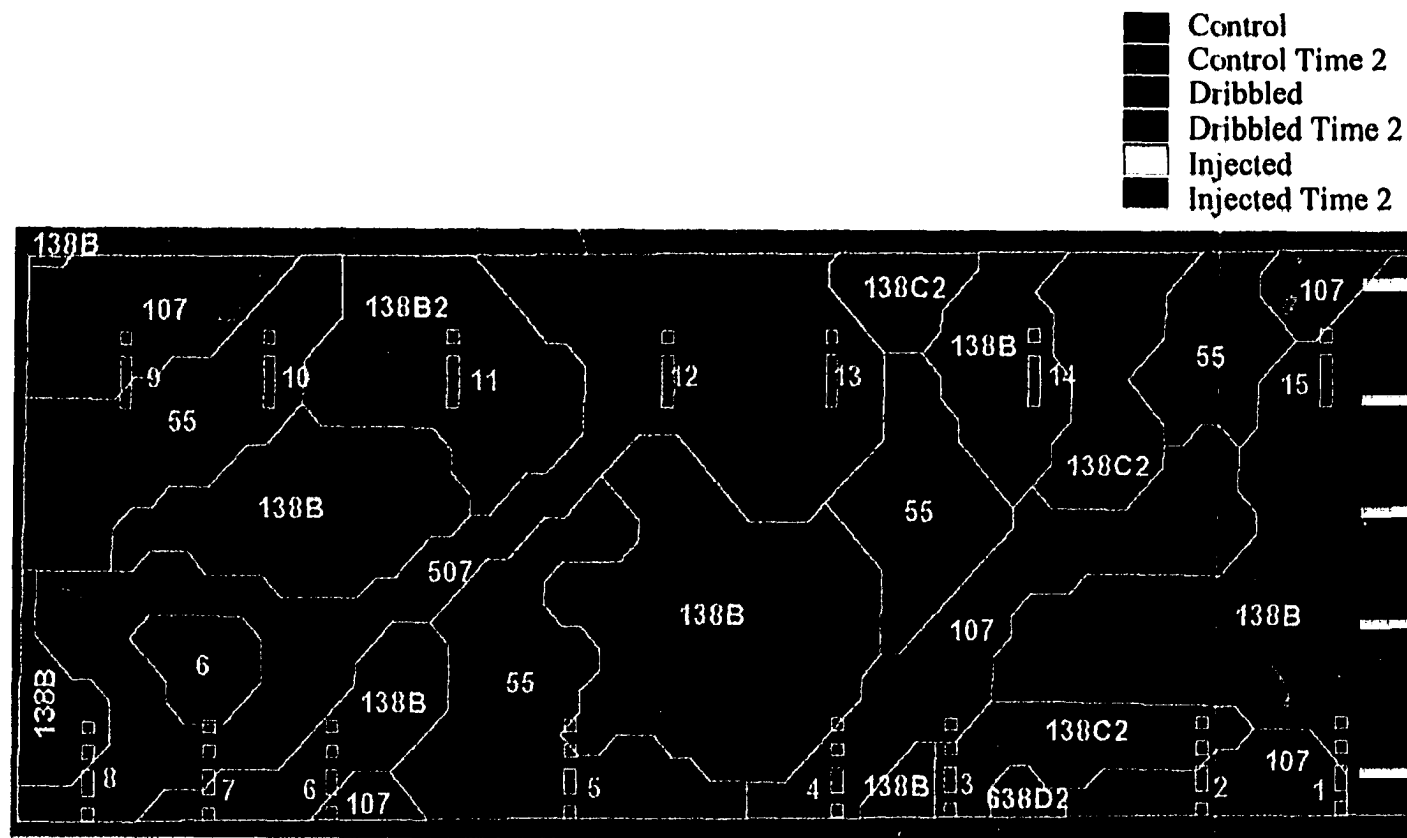


Figure 1. Location of test areas, soil types, and treatment locations for site 1 during 1999.

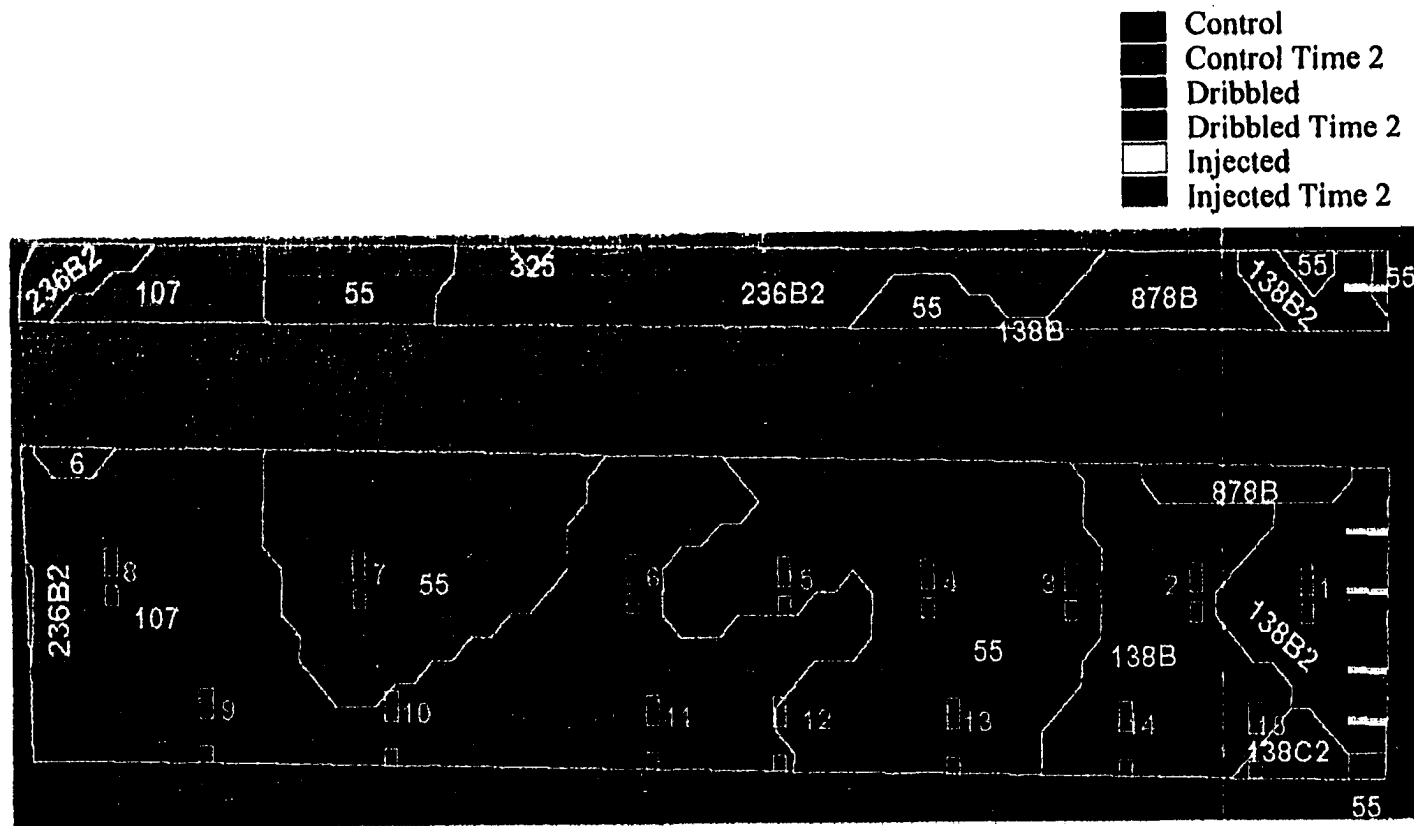


Figure 2. Location of test areas, soil types, and treatment locations for site 2 during 1999.

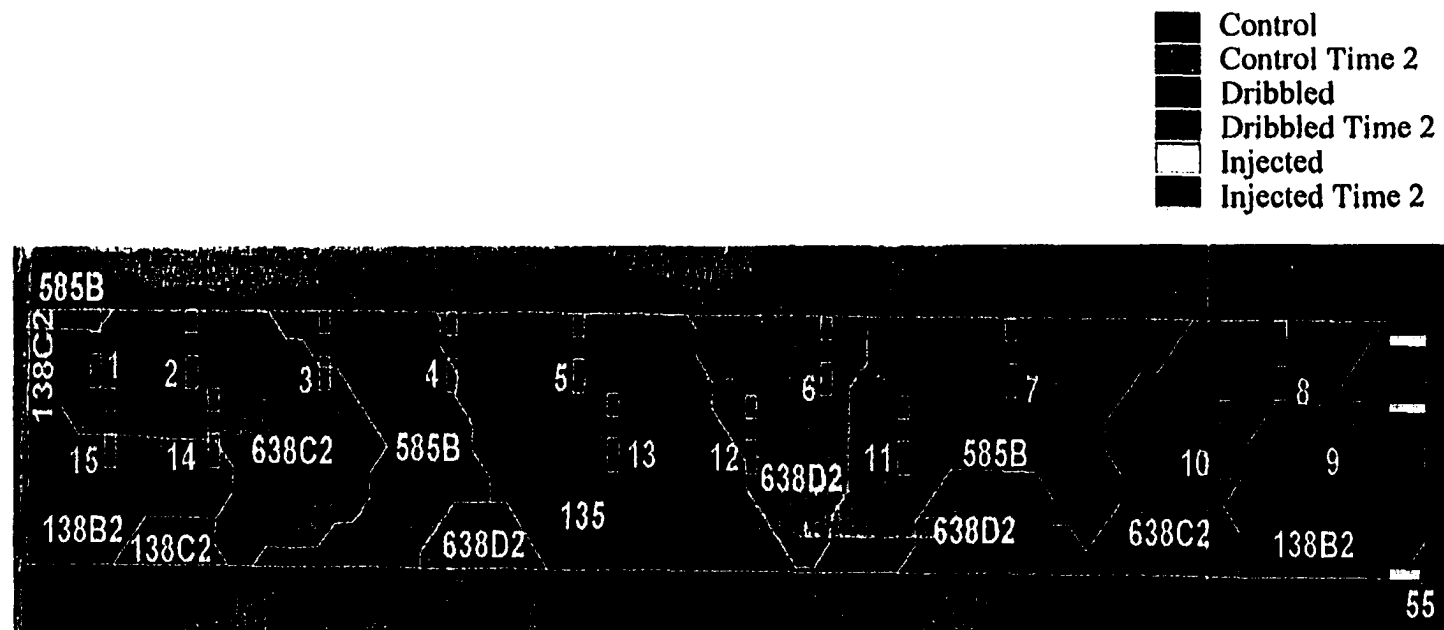


Figure 3. Location of test areas, soil types, and treatment locations for site 3 during 1999.

## GENERAL CONCLUSION

Nitrogen sufficiency levels are affected by soil characteristics, times and methods of application, losses that occur after application (denitrification, leaching, or volatilization), and weather after application. The effects of a specific factor are difficult to distinguish from the effects of other factors due to complex interactions between all factors. The ability of site-specific tools and precision farming technologies to evaluate the combined effects of all factors after they have been exhibited increases our ability to identify management practices that result in optimal sufficiency levels. Three studies were conducted that utilized site-specific tools and precision farming technologies to determine N sufficiency levels resulting from different N management practices during corn production.

The first study described how a survey-type approach using the late-spring soil nitrate test and the end of season cornstalk test can be used to evaluate N sufficiency levels, within similar geographic locations, to identify the best N management practices. This type of approach allows N recommendations to be developed that are specific for a location as opposed to general recommendations that may not apply. Recommendations that are more site-specific have the potential to increase N efficiency, while improving environmental quality.

The results of soil and cornstalk nitrate concentrations measured from production agriculture fields collected over a period of eight years showed considerable agreement within years. The agreement between the nitrate concentrations measured by two independent methods enhances the reliability of observations obtained by either method. The annual mean concentrations of soil and cornstalk nitrates tended to decrease with mean amounts of rainfall and amounts of water that flowed through major rivers in Iowa. These

findings reveal how weather can impact the effects of N management practices and illustrate the potential of an outcomes-based approach to evaluate the importance of these effects.

The second study described a new method to evaluate the effects of liquid swine manure on soil N mineralization rates after application instead of estimating the manure N mineralization rates. This type of approach enables the effects of manure applications to be examined under field conditions and distinguishes these effects from background soil mineralization to determine the magnitude of the contribution of additional N from manure.

Results showed that the net effects of manure on mineralization were small compared to the effects of inorganic N in manure, amounts of N lost or immobilized, and amounts of N mineralized from soil organic matter. These findings do not imply that the cumulative effects of manure applications would not result in a greater contribution from liquid swine manure. There was evidence that losses of N occurred soon after application of manure. The implications of these findings provide an opportunity to impact N management by not over-estimating N contributions from liquid swine manure and stressing the need to delay N applications until plants can utilize the N more effectively. These findings are specific for the type of manure used in this study and the field conditions encountered when the study was conducted. However, this approach demonstrates how evaluations of other animal manures for different soil conditions could be conducted.

The third study used precision farming technologies to evaluate times and methods of additional N applications to correct N deficiencies that occur after fall-applied N applications. As mentioned previously, time of N application influences N efficiency, and method of application affects losses, costs, and time required to apply additional N.

Evaluations of comparisons between these N management strategies can help producers to identify which practices result in maximum profits and decreased environmental degradation.

Nitrogen deficiencies were detected after fall-applied N. Responses to additional N were observed for yields, grain protein concentrations, and canopy reflectance values. Times of application or dribbled and injected applications of additional N revealed no differences at any site examined. One site revealed that yield responses could be categorized according to calcareous and non-calcareous areas. Identification of responsive and non-responsive areas within a field is possible by utilizing precision farming technologies. Such site-specific information can significantly improve N management by potentially decreasing average rates of fertilization due to the increased efficiency of N as a result of identifying the best fertilization practices.

All three studies provided evidence indicating that early season losses of N occur. However, these studies demonstrate how producers can benefit from this knowledge by revising their management practices. Delaying N application until just prior to rapid uptake begins will enable producers to increase N efficiency allowing a decrease in average rates of N fertilization while preventing environmental degradation of surface and groundwater supplies.

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